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ABSTRACT

This course in fluid power systems is one of 16 courses in the Energy Technology Series developed for an Energy Conservation-and-Use Technology curriculum. Intended for use in two-year postsecondary technical institutions to prepare technicians for employment, the courses are also useful in industry for updating employees in company-sponsored training programs. Comprised of eight modules, the course provides an overview of fluid power technology and a working of each of the components used in fluid power circuits. Hydraulic and pneumatic systems are discussed with emphasis placed on troubleshooting and maintenance procedures involved in each. Written by a technical expert and approved by industry representatives, each module contains the following elements: introduction, prerequisites, objectives, subject matter, exercises, laboratory materials, laboratory procedures (experiment section for hands-on portion), data tables (included in most basic courses to help students learn to collect or organize data), references, and glossary. Module titles are Introduction and Fundamentals of Fluid Power Properties and Characteristics; Fluid Storage, Conditioning, and Maintenance; Pumps and Compressors; Actuators and Fluid Motors; Fluid Distribution and Control Devices; Fluid Circuits; and Troubleshooting Fluid Circuits. (YLB)

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FLUID POWER SYSTEMS

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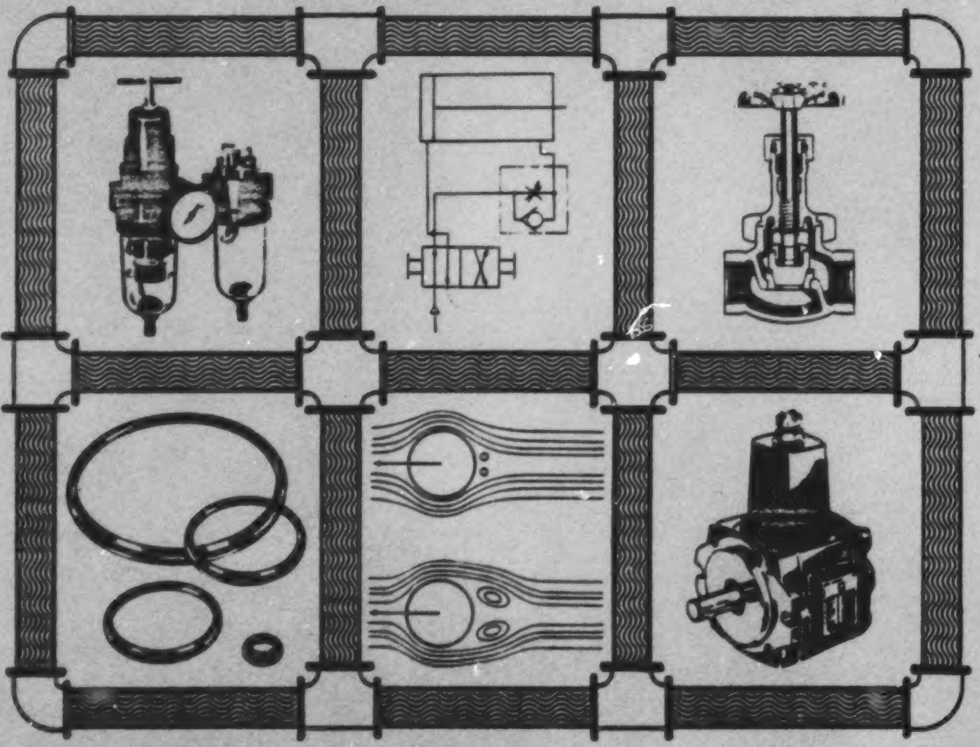

MODULE FL-01

INTRODUCTION AND FUNDAMENTALS OF FLUID POWER

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CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

Fluid power is the technology of transmitting power by means of pressurized fluids. It was one of the first power sources used by man, was one of the earliest industrial power distribution systems, and is widely used today in modern power handling systems. Fluid power systems may use either a liquid (hydraulic) or a gas (pneumatic) as an energy transfer medium.

This module discusses the advantages and disadvantages of fluid power, outlines the basic components and configurations of both pneumatic and hydraulic power systems, introduces fluid power symbols and circuits, and includes a review of basic principles of physics that apply to fluid power technology. Physics concepts discussed include pressure, force, work, and power as they relate to fluid power calculations; the basic principles of fluid behavior; and the characteristics of compressible and incompressible fluids. The fundamentals of fluid power presented in this module are the bases of all fluid power applications. These fundamentals are expanded in later modules.

The laboratory for this module consists of an exercise in which the student constructs and operates a simple hydraulic circuit and a simple pneumatic circuit and then compares the operation of the two.

PREREQUISITES

The student should have completed one semester of algebra and one semester of technical physics.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the following terms:
   a. Fluid power
   b. Hydraulics
   c. Pneumatics
   d. Hydrodynamics
   e. Hydrostatics
2. List at least six advantages and four disadvantages of fluid power as compared to other power delivery systems.

3. Draw diagrams showing the components of a basic hydraulic power system and a basic pneumatic power system. Label each component and describe its function within the system.
4. Given any two of the following quantities for a fluid power cylinder, calculate the third:
    a. Pressure
    b. Piston area
    c. Force
5. Given any two of the following quantities for a fluid power cylinder, calculate the third:
    a. Pressure
    b. Volume displacement
    c. Work done
6. Given any two of the following quantities for a fluid power system, calculate the third:
    a. Pressure
    b. Volume flow rate
    c. Power
7. Describe each of the following principles of fluid behavior and explain how it relates to fluid power systems:
    a. Pascal's law
    b. The continuity equation
    c. Bernoulli's theorem
    d. Torricelli's theorem
    e. Boyle's law
    f. Charles' law
8. Draw schematic diagrams, showing all components and connections, of hydraulic and pneumatic circuits for operating one single-acting cylinder.
9. Construct the fluid circuits in Objective 8 and operate them in the laboratory.

INTRODUCTION TO FLUID POWER

Fluid power is a technology that deals with the transmission and control of energy by means of pressurized fluids. Fluid power systems that use incompressible fluids (liquids) are called hydraulic systems. Those that use compressible fluids (gases, usually air) are called pneumatic systems. In either case, the fluid power system operates in the following manner: it adds potential energy to a fluid at one location by increasing its pressure, it moves the fluid to another location, and it recovers the energy for useful work by lowering the fluid pressure.

The term "hydrodynamics" refers to the behavior of fluids in motion; the term "hydrostatics" describes the behavior of fluids at rest in an equilibrium condition. This definition seems to imply that the study of fluid power would depend heavily on hydrodynamics since energy is to be moved by moving a fluid and would depend less on hydrostatics since a fluid that is not moving cannot transmit continuous power. However, this is not the case. Most of the energy contained within the fluid is in the form of the potential energy of increased pressure, not in the kinetic energy of motion. Hydrodynamics is useful to study since it describes the effects of resistance to flow, turbulence, and pump design; but the interest is always on lessening the hydrodynamic energy losses. Practical fluid power systems are designed to have relatively low fluid velocities; therefore, their hydrodynamic properties are of little importance to system operation. Since fluid power depends on transmitting energy through small fluid flow rates at high pressure, it is much more dependent on hydrostatics. The basic principles of hydrostatics — as they apply to fluid power — are discussed later in this module.

BACKGROUND AND APPLICATIONS OF FLUID POWER

Applications of fluid power are probably as old as civilization itself. Ancient history contains many accounts of the use of moving water and air to power waterwheels, windmills, and ships. The first scientific basis of fluid power technology was investigated by Pascal in about 1650. His discoveries eventually led to the development of fluid power systems and to the development of steam and internal combustion engines. Pascal's law is described later in this module.

Fluid power was first applied as an industrial technology in the Industrial Revolution in Great Britain in 1850. By 1870, the use of hydraulic systems to drive machinery was common. The development of electricity in the late nineteenth century lessened the interest in fluid power, although its use did continue. The development of modern fluid power technology began in World War II with an increase in the use of fluid power in naval vessels, in aircraft, and later in production machinery. Modern fluid power systems are essential parts of most industrial processes and most mobile power systems.

One of the largest applications of fluid power is in the transportation industry. Automobiles employ fluid power for the operation of hydraulic brakes, power steering, and other accessories. Aircraft and marine vessels use hydraulic controls.

Fluid power is also used in a wide variety of applications involving moving large loads. This includes ditchdigging and earth-moving equipment, cranes, and construction equipment. Any industrial application requiring large forces is a candidate for fluid power since no other power system can conveniently produce such large forces. Large fluid power systems operate presses, forges, and milling equipment. Fluid power is as common as electrical power in many modern industries.

ADVANTAGES AND DISADVANTAGES OF FLUID POWER

The suitability of fluid power for any power application is dependent upon several advantages and disadvantages of fluid power, as compared to other forms of power delivery.

ADVANTAGES

Major advantages of fluid power include the following:

1. The fluid, whether gaseous or liquid, will remove heat generated during the power application. Thus, for many applications, the cooling problems are much less severe than with electric motors.
2. A hydraulic device is mechanically rigid with respect to the load. It can position and hold loads without a mechanical lock, even after the power source has been turned off. This is also true of some pneumatic devices, but not all.
3. Fluid power devices are highly responsive due to their high power-to-weight ratio.

4. Fluid power devices are much easier to install than mechanical power transmission equipment. They occupy a minimum of space and are easily controlled from a remote location.
5. Fluid power devices offer great control of power application. They are reversible and may be operated at either constant or variable power in either direction.
6. Fluid power control may be easily accomplished by a wide range of control modes (mechanical, electrical, fluidal).
7. Force multiplication can be accomplished with low power losses.
8. Fluid power often permits simplification of machine design and reduced maintenance.
9. Fluid power may be used safely in environments that make the use of electricity hazardous.

DISADVANTAGES

Major disadvantages of fluid power include the following:

1. Hydraulic fluids are messy, and they attract and hold dirt.
2. All fluid power systems are susceptible to damage by dirt or contamination. Careful design and workmanship and a good maintenance program are essential. Mechanical and electrical systems can continue to function with far less attention.
3. Conductor failure because of overpressure or mechanical stress is always possible; this presents a serious safety problem.
4. Most common hydraulic fluids are combustible and present fire hazards.

BASIC FLUID POWER SYSTEMS

Although fluid power systems vary greatly in size and sophistication, all may be classed as either hydraulic or pneumatic. However, each of these two classes has certain common components and configurations. This section of the module discusses the basic components and characteristics of hydraulic and pneumatic systems.

HYDRAULIC SYSTEMS

Figure 1 shows a typical hydraulic system using an incompressible liquid as the power transfer fluid. The liquid is contained in a reservoir at atmospheric pressure. The liquid is drawn through a filter to remove contaminants to the pump of the system. The pump may be driven by any convenient source of rotational mechanical energy -- such as an electric motor, a gasoline engine, or a steam turbine. The pump, which is of the positive-displacement type, delivers liquid at a constant flow rate within its rated pressure range. The pump provides no pressure control, and it has a fixed delivery rate. It converts mechanical energy to potential energy of a liquid under pressure.

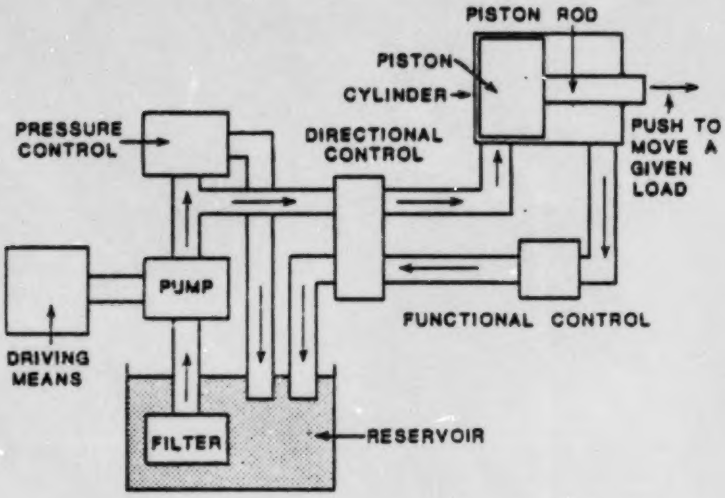


Figure 1. Typical Hydraulic System.

Pressure is controlled by a pressure control device called a pressure relief valve. This valve remains closed below a certain pressure; but at the preset delivery pressure, it opens to allow liquid to flow directly back to the reservoir. If no other fluid path exists, all of the pump output flows through this valve. Thus, this device protects the pump and the rest of the system from overpressure conditions and maintains the proper operating pressure. The reservior, pump, filter, and pressure control comprise the fluid power source.

Several types of devices may be operated by fluid power, but the simplest and most common is a cylinder containing a piston. The piston shown in Figure 1 is a double-acting cylinder that can be powered in either direction, depending on the direction of fluid flow to the cylinder. In either direction, the force produced by the pressurized liquid causes the piston to exert a force on the load.

The action of the piston is controlled by two types of control valves. Directional control valves are used to control the direction of flow to and from the piston. They are usually capable of directing hydraulic fluid to either end of the cylinder or of shutting off the flow completely, although one of these functions may be excluded. Functional controls may be used to control the rate of fluid flow in a particular part of the system or to produce sequential operation of the components.

In a hydraulic system, the speed of operation of any driven component depends upon the rate at which the pump can deliver liquid to fill that component. Changing the pressure setting will change the maximum force produced, but will not change the operating speed of a cylinder.

PNEUMATIC SYSTEMS

Figure 2 shows a typical pneumatic power system using air (a compressible gas) as the power transfer fluid. One major advantage of this sytem is that air may be drawn directly from the atmosphere and exhausted into the atmosphere when used. This eliminates the need for return lines and a reservoir containing the working fluid. The chief disadvantages — as compared to a hydraulic sytem — are the need to clean and condition the air and the lack of positive-displacement control because of the compressibility of the working fluid.

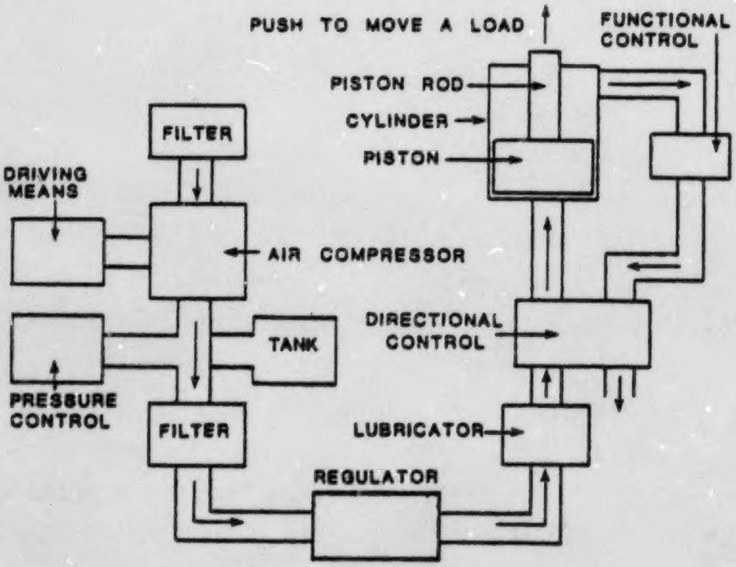

PUSH TO MOVE A LOAD
FUNCTIONAL CONTROL
PISTON ROD
CYLINDER
PISTON
FILTER
DRIVING MEANS
AIR COMPRESSOR
DIRECTIONAL CONTROL
TANK
PRESSURE CONTROL
FILTER
LUBRICATOR
REGULATOR

Figure 2. Typical Pneumatic System.

In the pneumatic system, air enters the compressor through an intake filter. The compressor increases the density, pressure, and potential energy of the air. Most compressors are of the positive-displacement type, delivering a constant volume flow of air. The compressor is often followed by a storage tank containing pressurized air that acts as a power source when the compressor is not in operation. This relative ease of storing energy for later use is one of the major advantages of pneumatic power systems, although the same principle can be applied to hydraulic systems.

The pressure control of the pneumatic system may function in one of three ways:

1. It may allow excess air to escape to the atmosphere in much the same way that the pressure relief valve of the hydraulic system allows excess fluid to flow into the reservoir.
2. It may regulate compressor power or intake volume.
3. It may turn the compressor on and off at preset pressures for systems employing storage tanks.

The compressor, pressure control, and associated equipment comprise the fluid power source. Compressed air from this source is distributed for power applications.

Air distribution systems are susceptible to condensation, dirt, and scale in the pipes. This foreign matter must be removed before the air can be used, and the air must be conditioned. Three devices accomplish air conditioning:

1. A filter removes water and dirt.
2. A pressure regulator supplies air at a constant, preset pressure independent of fluctuations in delivery line pressure.
3. A lubricator injects oil for lubricating and sealing the driven device. These lubricators are usually contained in a single unit (FRL unit) located near the driven device.

The pneumatic cylinder, directional controls, and functional controls are similar to those of the hydraulic system.

In a pneumatic system, the speed of operation of a driven component may increase with increasing pressure because the working fluid is compressible. The air expands to produce a delivery rate to the driven component that exceeds the fixed delivery of the compressor — particularly if the system contains a storage tank, as most do. This may lower system pressure for a short time; but, if the total system volume greatly exceeds the volume of the component, the effect is slight. Thus, increasing the pressure of a pneumatic system increases both the maximum force available and the operating speed of components against a fixed mechanical resistance.

REVIEW OF PHYSICS FUNDAMENTALS

Fluid power systems transfer energy from one place to another for application. This section of the module reviews some basic principles of physics as they relate to energy transfer in fluid power systems.

FORMS OF ENERGY

Energy is the ability to do work, to cause change, or to produce motion in a physical system. In industrial applications, this energy is usually mechanical, electrical, thermal, or fluidal. Fluid power systems are designed to deliver energy in the form of fluidal energy, but they always involve other types of energy as well. Pumps and compressors convert the kinetic energy (mechanical rotational energy) of the moving components to potential energy of the pressurized fluid. The input energy to the pump may be supplied by an electric motor or a heat engine. The output energy of fluid power systems is always mechanical motion. Fluid power controls operate through the application of mechanical, electrical, thermal, or fluidal input signals. The presence and flow of heat energy in fluid power systems is often of great importance. In short, a fluid power system is always composed of components that utilize other types of energy and is always integrated into a larger system as a power delivery subsystem. Fluid power never exists in isolation. Since the basic operation of fluid power systems consists of transmitting fluid power and of power conversions between mechanical and fluidal systems, only those basic principles are presented here.

FORCE AND PRESSURE

Pressure is defined as "the force per unit area exerted by a fluid." In fluid power applications, pressure is usually measured in pounds per square inch and is expressed in gauge pressure (atmospheric = 0 psig) rather than absolute pressure (atmospheric = 14.7 psia). The force produced on a surface by a fluid is given in Equation 1.

$$F = pA \qquad \text{Equation 1}$$

where: F = Force, in pounds.
p = Pressure, in pounds per square inch.
A = Area, in square inches.

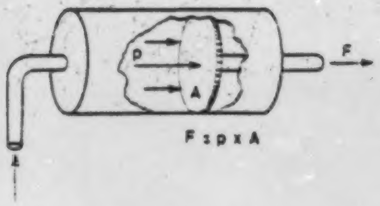
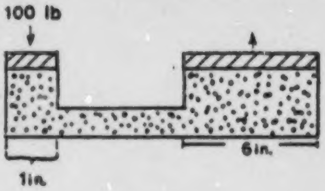


Figure 3. Relationship of Force, Pressure and Area.

Figure 3 shows the application of this equation to fluid power. The force produced on the piston is the product of the pressure of the fluid and the area of the cylinder. Example A illustrates the application of this principle in a simple fluid system for force multiplication.

EXAMPLE A: FORCE MULTIPLICATION IN A HYDRAULIC LIFT.

Given: A hydraulic lift has an input cylinder of 1 inch in diameter and an output cylinder 6 inches in diameter. A downward force of 100 lb is applied to the input piston. Assume this produces a pressure that is equally distributed throughout the liquid.



Find:
a. The pressure.
b. The upward force on the output piston.

Solution: Find cylinder areas.

$$A = \frac{\pi d^2}{4}$$

$$A_1 = \frac{(3.14)(1.0\ \text{in})^2}{4} \qquad A_2 = \frac{(3.14)(6\ \text{in})^2}{4}$$

$$A_1 = 0.785\ \text{in}^2 \qquad A_2 = 28.26\ \text{in}^2$$

a. From Equation 1:

$$P_1 = \frac{F_1}{A_1}$$

$$= \frac{100\ \text{lb}}{0.785\ \text{in}^2}$$

$$P_1 = 127.4\ \text{psig}\ (\text{lb/in}^2 = \text{psig}).$$

b.

$$F_2 = P_2 A_2$$

$$= (127.4\ \text{psig})(28.26\ \text{in}^2)$$

$$F_2 = 3600\ \text{lb}.$$

WORK DONE BY A FLUID

Figure 4 illustrates the work done by a fluid on a piston. The work done is equal to the potential energy removed from the fluid and converted to mechanical work done by the piston. Equation 2 gives the work done by a piston under constant load.

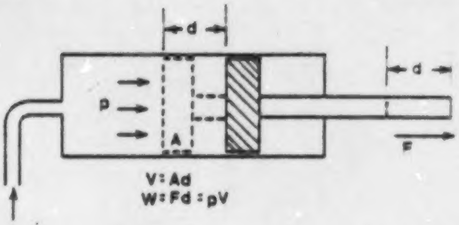


Figure 4. Work Done by a Fluid.

$$W = Fd = pV \qquad \text{Equation 2}$$

where: W = Work done.
F = Force on piston.
d = Displacement of piston.
p = Fluid pressure.
V = Change in fluid volume in cylinder (the product of the piston area and displacement).

Example B illustrates the application of Equation 2 in calculations involving the input and output energy of a simple fluid system.

EXAMPLE B: WORK DONE BY A HYDRAULIC LIFT.

Given: The input piston of the lift in Example A is pushed downward a distance of 1 ft by the applied force of 100 lb. (Assume no energy losses.)

Find:
a. The work done on the liquid by the input piston.
b. The volume of fluid transferred.
c. The upward displacement of the output piston.

Solution: a.

$$\begin{aligned} W &= Fd \\ &= (100\text{ lb})(1\text{ ft}) \\ W &= 100\text{ ft}\cdot\text{lb}. \end{aligned}$$

Example B. Continued.

b. $V = \frac{W}{p}$

$= \frac{(100\ \text{ft}\cdot\text{lb})(12\ \text{in/ft})}{127.4\ \text{lb/in}^2}$

$V = 9.4\ \text{in}^3$.

This is the volume of a cylinder 1 inch in diameter and 1 foot in length.

c. $d = \frac{W}{F}$

$= \frac{100\ \text{ft}\cdot\text{lb}}{3600\ \text{lb}}$

$= 0.028\ \text{ft}$

$d \simeq 1/3\ \text{in.}$

As Example B illustrates, the multiplication of force in a fluid system is accompanied by a corresponding division of displacement.

TORQUE AND WORK

In many fluid power systems, the output power is in the form of rotational energy instead of linear mechanical motion. Input mechanical energy to fluid power systems is almost always rotational energy to drive a pump or compressor. Torque is the forcelike quantity of mechanical rotational systems and produces rotational motion as force produces linear motion. Figure 5 illustrates the definition of torque. It is the product of the force and the perpendicular distance through which it acts (the lever arm). The rotational work done by a shaft is given by Equation 3.

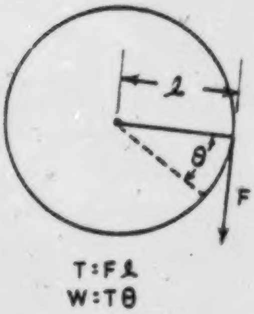


Figure 5. Torque and Work.

$$W = T\theta \qquad \text{Equation 3}$$

where: W = Work done.

T = Torque.

θ = Angle of rotation of the shaft.

POWER IN FLUID POWER SYSTEMS

Power is the rate at which work is done. Power may be calculated in any system by dividing the energy transferred by the time required for the transfer. Figure 6 shows three expressions for power at three different points in a fluid power system. The input power produced by the pump is its torque times its angular velocity (θ/t). The fluid power transferred through the conductor is the pressure times the volume flow rate (V/t). The mechanical power of the piston lifting the load is the weight (force) of the load times its upward velocity (h/t). The most important relationship in fluid power applications is shown in Equation 4.

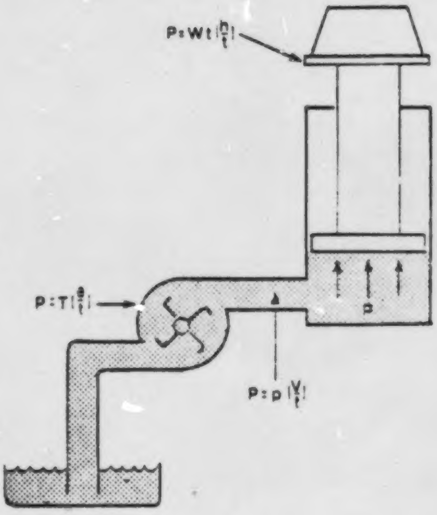

$P = Wt\left(\frac{h}{t}\right)$
$P = T\left(\frac{\theta}{t}\right)$
p
$P = p\left(\frac{V}{t}\right)$

Figure 6. Power in a System.

$$P = pQ \qquad \text{Equation 4}$$

where: P = Power.
p = Pressure.
Q = Volume flow rate.

Example C illustrates the use of this equation.

EXAMPLE C: CALCULATION OF PUMP POWER.	
Given:	The operation of a hydraulic power system requires 4 gallons of fluid per minute at a pressure of 400 psig. $(1 \text{ gal} = 231 \text{ in}^3)\ (1 \text{ hp} = 550 \frac{\text{ft}\cdot\text{lb}}{\text{sec}})$
Find:	The necessary power of the pump motor.
Solution:	Determine volume flow rate in cubic inches per second. $Q = (4 \text{ gal/min})(\frac{1 \text{ min}}{60 \text{ sec}})(\frac{231 \text{ in}^3}{\text{gal}})$ $Q = 15.4 \text{ in}^3/\text{sec}$

Example C. Continued.

$$\begin{aligned}
\text{Power:}\quad P &= pQ \\
&= (400\ \frac{\text{lb}}{\text{in}^2})(15.4\ \frac{\text{in}^3}{\text{sec}}) \\
&= (6160\ \frac{\text{in}\cdot\text{lb}}{\text{sec}})(\frac{1\ \text{ft}}{12\ \text{in}}) \\
&= 513\ \frac{\text{ft}\cdot\text{lb}}{\text{sec}} \\
&= (513\ \frac{\text{ft}\cdot\text{lb}}{\text{sec}})(\frac{1\ \text{hp}}{550\ \frac{\text{ft}\cdot\text{lb}}{\text{sec}}}) \\
P &= 0.93\ \text{hp.}
\end{aligned}$$

A one-horsepower pump will operate this system if losses are low.

BASIC PRINCIPLES OF FLUID BEHAVIOR

The characteristics of a fluid power system are dependent upon the characteristics of the fluid used. This section discusses some of the properties of liquids and gases that are of interest in fluid power applications.

PASCAL'S LAW

Pascal's law applies to both liquids and gases. It states that a pressure set up in a fluid in an enclosed container produces an equal force on all surface elements of equal size and that the force is always perpendicular to the surface. As illustrated in Figure 7, this means that the pressure is the same at all points within an enclosed static fluid. Pascal's law is the basis of fluid power transfer. It is essential for the operation of the hydraulic lift in Example A.

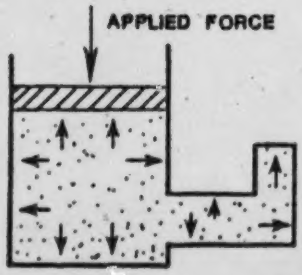


Figure 7. Pascal's Law.

THE CONTINUITY EQUATION

The continuity equation, which only applies to liquids, is illustrated in Figure 8. The continunity equation states that when a liquid flows through a conductor with no branches, the volume flowing past any two points in a given period of time is the same. The shaded portions of the figure represent the volumes of fluid flowing in the larger and smaller sections of the pipe during a time interval. The volume flow rate is the product of the fluid velocity (v) and the cross-sectional area of the pipe. For a given volume flow rate, large diameter pipes provide lower fluid velocities and less frictional losses.

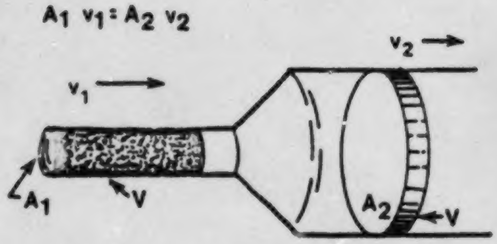


Figure 8. Continuity Equation.

BERNOULLI'S THEOREM

Bernoulli's theorem is an application of the conservation of energy to fluid systems. It states that the total energy per unit mass of a fluid in a closed conductor is the same at all points. This energy is the sum of three components: the potential energy of the fluid due to its pressure, the kinetic energy of the fluid because of its motion (velocity), and the potential energy due to gravity. If the case of a horizontal pipe is considered, the gravitational factor may be dropped (and is usually not a factor in fluid power systems).

Figure 9 illustrates Bernoulli's theorem as it applies to fluid power systems. The velocity of the fluid varies as the conductor size varies with higher velocity in the smaller sections. The increased velocity means greater kinetic energy per unit mass and, thus, reduced potential energy. Since the potential energy per unit mass is directly related to the pressure, the pressure is also reduced. Thus, the pressure in a conductor carrying a moving liquid drops as the diameter decreases, and constrictions produce low pressure areas. This principle is applied in the lubricators of pneumatic systems to draw oil into a constricted air stream.

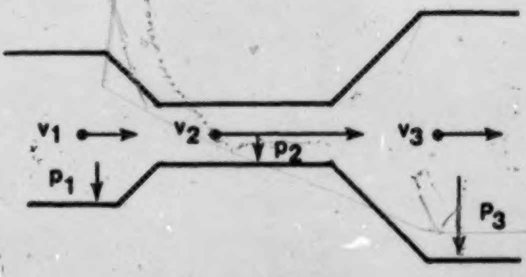


Figure 9. Bernoulli's Theorem.

TORRICELLI'S THEOREM

Figure 10 illustrates Torricelli's theorem — which states that the velocity of the fluid leaving a hole in the bottom of a large tank is equal to the square root of twice the product of the height of the tank and the gravitational constant. The importance of this theorem to fluid power technology is that this condition is a good approximation of a small leak in a pressurized fluid system, and it allows calculation of the approximate velocity of escaping fluid should a leak occur. This is included primarily to emphasize the hazards of leaks. If the system pressure is only 100 psig, the velocity of an escaping fluid jet is 120 ft/sec.

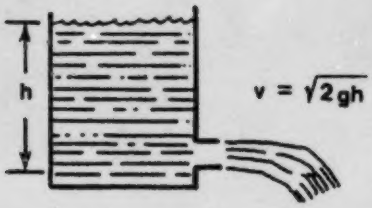


Figure 10. Torricelli's Theorem.

GAS LAWS

The gas laws are a series of laws concerning the behavior of a gas as its volume, pressure, and temperature change. The relationships are illustrated in Figures 11, 12, and 13.

The most important gas law in pneumatic systems is Boyle's law (Figure 11). This law states that, at a constant temperature, the product of the pressure and volume of a gas is a constant — if one is increased, the other is decreased proportionally. Thus, if a compressor reduces the volume to one-tenth the volume of the same mass of free air, it multiplies the original pressure by 10. (All gas laws are based on absolute temperature and pressure scales.)

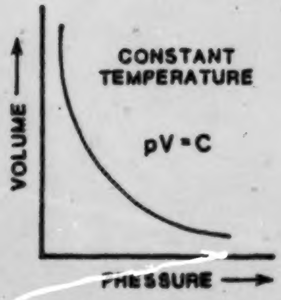


Figure 11. Boyle's Law.

Charles' law (Figure 12) states that, at a constant pressure, the ratio of gas volume to gas temperature is a constant. Thus, the volume occupied by a gas at a given pressure decreases as the temperature decreases. This means that reducing the compressed air temperature allows more air and, thus, more useful energy to be stored in a smaller volume.

Figure 13 shows the pressure-temperature relationship of a gas at a constant volume. This law, called Gay-Lussac's law, states that the pressure of an enclosed gas rises in proportion to its increase in temperature. This law is of greater importance in combustion engines and boilers than in fluid power applications and is included primarily for completeness.

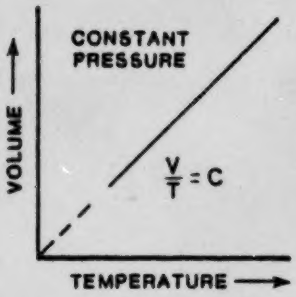


Figure 12. Charles' Law.

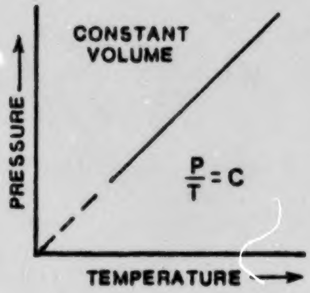


Figure 13. Gay-Lussac's Law.

These three relationships are combined in the general gas law given by Equation 5.

$$\frac{PV}{T} = C \qquad \text{Equation 5}$$

where: P = Absolute pressure.
V = Volume.
T = Absolute temperature.
C = A constant.

Equation 5 shows the relationship of pressure, volume, and temperature; and it illustrates that changing any one of these quantities produces a change in one or both of the other two. Any of the three individual gas laws may be derived from the general law by eliminating the quantity that is assumed to be constant.

BASIC FLUID CIRCUITS AND SYMBOLS

The American National Standards Institute, Inc., has approved a standard set of fluid power symbols for diagramming fluid power systems. This section of the module introduces some of the basic symbols and illustrates the basic fluid circuits to be constructed in the Laboratory portion of this module.

HYDRAULIC CIRCUIT

Figure 14 is a simple hydraulic circuit for operating one single-acting cylinder (hydraulic power applied in one direction only). This is the most basic hydraulic circuit. Each of the symbols is identified in the figure. This type of directional control valve is called a three-way valve because it has three fluid connections. It is also termed a "two-position valve" because it has two possible operating positions. The fluid paths for each position are shown in the valve symbol. In the closed position, the power line (P) is blocked and the cylinder is connected to the tank line (T). Thus, the return spring of the cylinder forces the fluid into the reservoir. When the valve is operated, the tank line is blocked and the power line is connected to the cylinder. Many other types of directional control valves are common. These valves will be discussed in greater detail in Module FL-06, "Fluid Distribution and Control Devices."

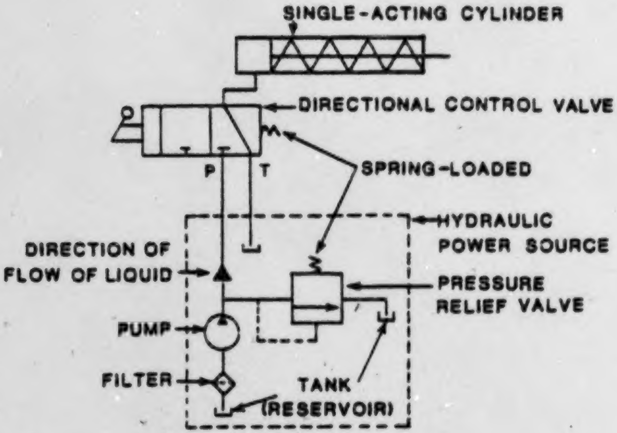


Figure 14. Hydraulic Circuit for Operating One Single-Acting Cylinder.

PNEUMATIC CIRCUIT

Figure 15 is a simple pneumatic circuit for operating one single-acting cylinder. Basic symbols are also identified in this figure. The needle valves are used to control the flow rate of compressed air to and from the cylinder. Adjusting these valves changes the extension and retraction times of the cylinder. With the directional control valve (DCV) in the closed position, the cylinder is connected to atmospheric pressure and is retracted by the return spring. The power line is blocked inside the valve. In the open position, the power line is connected to the cylinder through the valve.

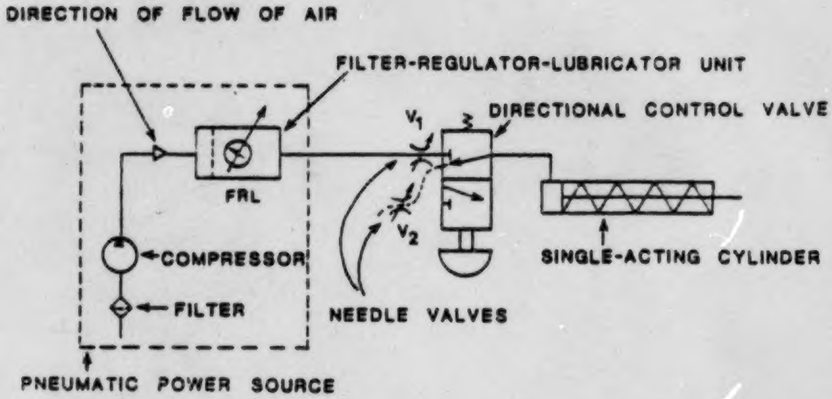

DIRECTION OF FLOW OF AIR
FILTER-REGULATOR-LUBRICATOR UNIT
V_1
DIRECTIONAL CONTROL VALVE
FRL
V_2
SINGLE-ACTING CYLINDER
COMPRESSOR
FILTER
NEEDLE VALVES
PNEUMATIC POWER SOURCE

Figure 15. Pneumatic Circuit for Operating One Single-Acting Cylinder.

SUMMARY

Fluid power systems are energy transfer systems in which mechanical energy is converted to potential energy of pressurized fluids, is moved to a remote point as fluidal potential energy, and is converted back into mechanical energy for application. Fluid power systems have several advantages over other power delivery systems and are widely used in transportation and industry. Hydraulic systems use a liquid contained in a closed fluid system. Pneumatic power systems use air as a working medium and need not recirculate the fluid. The most important physical principle in fluid power technology is that the force produced on a surface is equal to the product of the area of the surface and the pressure applied by the fluid.

EXERCISES

1. List nine advantages and four disadvantages of fluid power.
2. Draw and label diagrams showing the basic components of a hydraulic power system and a pneumatic power system. Explain the purpose of each component.
3. A hydraulic cylinder 4 inches in diameter is operated at a pressure of 350 psig. In six seconds, the piston moves a distance of 8 inches. Determine the following:
   a. Force on the piston
   b. Work done by the piston
   c. Volume displacement of the cylinder (by two methods)
   d. Volume flow rate, in gal/min
   e. Power
4. A simple hydraulic lift has an input piston with a diameter of 1.5 inches and an output piston with a diameter of 8 inches. The force on the output piston is 3000 lb. Determine the following:
   a. Force on the input piston
   b. Distance each piston moves when 500 ft·lb of work is done
5. The fluid power rate of a fluid power system is 25 gal/min, and the pressure is 500 psig. Find the power.
6. A two-horsepower pump delivers hydraulic fluid at a pressure of 250 psig. It powers a cylinder 3.5 inches in diameter. Determine the following:
   a. Volume flow rate, in gal/min
   b. Velocity of the piston rod as it extends, in in/sec
7. Discuss each of the following principles of fluid behavior and its application to fluid power systems:
   a. Pascal's law
   b. Bernoulli's theorem
   c. Boyle's law
   d. Torricelli's theorem
   e. Charles' law
   f. The continuity equation

LABORATORY MATERIALS

All laboratories in this course will use common hydraulic and pneumatic components equipped with quick disconnect fittings. These will be mounted on a horizontal surface and secured with bolts or clamps. All connections will be made with flexible hydraulic and pneumatic hoses equipped with quick disconnects. The hydraulic power unit consists of a pump, reservoir, filter, adjustable pressure relief valve, and pressure gauge. The pneumatic power unit consists of a compressor, intake filter, and a filter-regulator-lubricator unit with a pressure gauge.

Hydraulic power unit
Hydraulic pressure relief valve
Hydraulic directional control valve (two-position, three-way, manually-actuated, spring offset)
Single-acting hydraulic cylinder with spring return
Hydraulic fluid flowmeter
Pneumatic air flowmeter
Connecting hydraulic hoses
Pneumatic power unit
Pneumatic directional control valve
Single-acting pneumatic cylinder with spring return
Connecting pneumatic hoses
Stop watch or timer
English scale (1 ft)
Loading devices for cylinders (This may consist of two disk brake pucks with adjusting screws to vary the pressure exerted on a metal bar that slides between the pucks. The metal frame containing the pucks must be bolted securely to the work surface.)

LABORATORY PROCEDURES

LABORATORY 1. HYDRAULIC EXPERIMENT.

1. Mount the directional control valve (DCV), pressure relief valve, cylinder, and flowmeter on the work surface for convenient connection and operation. The fluid circuit to be constructed is that shown in Figure 16. The hydraulic power unit is the portion of this figure enclosed in the box. The flow-

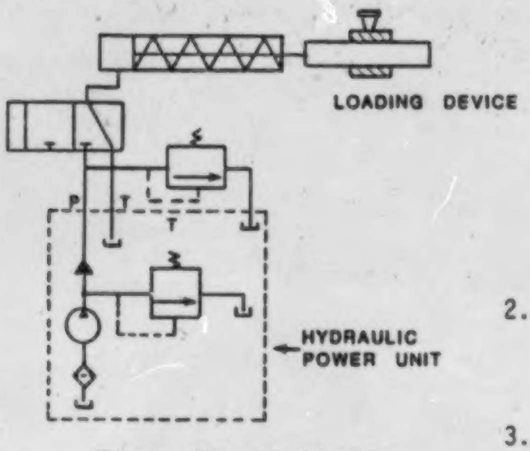


Figure 16. Hydraulic Experimental Setup.

meter is to be connected in series in the power line to the DCV. The pressure relief valve of the hydraulic power unit is preset and will not be adjusted. A second pressure relief valve installed by the student on the work surface is used for pressure adjustment by the student.

2. Use appropriate hoses to connect the circuit shown in Figure 16 with the flowmeter in the power line.
3. Connect the driving rod of the cylinder to the loading device. Be sure both the cylinder and the loading device are securely attached to the work surface.
4. Have the instructor check the circuit.
5. Turn on the hydraulic power unit. Set the pressure relief valve to give the desired pressure (specified by the instructor) as indicated by the pressure gauge of the power unit.
6. Activate the DCV to operate the cylinder. When the cylinder reaches the end of its travel, release the DCV actuator. This will check circuit operation and purge the lines and components of trapped air. Reduce the tension on the cylinder loading device to allow the piston to return if necessary.
7. Operate the circuit several times. Adjust the tension of the loading device to give a pressure near the preset pressure during cylinder operation. Measure and record the following quantities:
    a. Operating pressure
    b. Fluid flow rate
    c. Time for cylinder to extend
8. Set the pressure relief valve to the second specified pressure.
9. Repeat the above procedures and measurements at this pressure with the loading device adjusted to give an operating pressure near the preset pressure.
10. Measure the distance traveled by the piston during extension. Record in Data Table 1.

11. For each set of data, determine the volume of the cylinder by multiplying the volume flow rate times the time of extension (1 gal = 231 in^3). Divide the cylinder volume by the stroke to determine the cross-sectional area of the cylinder. Determine the inner diameter of the cylinder, using the equation for the area of a circle.
12. Describe the effect of changing the pressure on the extension time of the cylinder.
13. Disassemble the setup. Clean and store components according to instructions.

LABORATORY 2. PNEUMATIC EXPERIMENT.

1. Mount the DCV, cylinder, flowmeter, and two needle valves on the work surface for convenient connection and operation. The fluid circuit to be constructed is shown in Figure 15. The pneumatic power unit is the portion of this figure enclosed in the box. The flowmeter is connected in series in the power line, as it was in the hydraulic experiment.
2. Use the appropriate hoses to connect the circuit shown in Figure 15.
3. Install the cylinder loading device, as it was in the hydraulic experiment.
4. Have the instructor check the circuit.
5. Turn on the pneumatic power unit. Set the pressure regulator to the first specified pressure. Record this pressure in Data Table 2.
6. Actuate the DCV to assure proper circuit operation. Adjust the cylinder loading device so the spring will just retract the piston.
7. Operate the circuit several times. Change the settings of the needle valves and observe the effect on the extension and retraction times of the cylinder. Measure and record the air flow rate and the extension and retraction times at the final valve settings.
8. Set the pressure regulator to the second specified pressure. Do not change the settings of the needle valves or the cylinder loading device.
9. Operate the circuit. Measure and record the extension and retraction times and the air flow rate.
10. Describe the effect of changing the pressure on the extension and retraction times of the cylinder.
11. Disassemble, clean, and store all components.

DATA TABLES

DATA TABLE 1. HYDRAULIC EXPERIMENT.

	First Pressure	Second Pressure
Pressure (psig) Fluid flow rate (gal/min) Extension time (sec) Cylinder stroke (in) Calculated cylinder volume (in²) Calculated cylinder diameter (in)		
Effect of pressure on extension time:		

DATA TABLE 2. PNEUMATIC EXPERIMENT.

	First Pressure	Second Pressure
Pressure (psig) Air flow rate (cfm) Extension time (sec) Retraction time (sec)		
Effect of pressure on extension and retraction time:		

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Hardison, Thomas B. *Fluid Mechanics for Technicians*. Reston, VA: Reston Publishing Co., 1977.

Stewart, Harry L. *Pneumatics and Hydraulics*. Indianapolis, IN: Theodore Audel and Co., 1976.

Stewart, Harry L. and Storer, John M. *Fluid Power*. Indianapolis, IN: Howard S. Sams and Co., Inc., 1977.

GLOSSARY

Directional control valve (DCV): A valve that controls the direction of flow of fluid toward or away from the driven component.

Fluid power: The technology that deals with the transmission and control of energy by means of pressurized fluids.

Functional controls: Controls that effect the speed of operation of a fluid power device or the sequence of operations in a system.

Hydraulic system: Fluid power systems that use a liquid as a working medium.

Hydrodynamics: The study of liquids in motion.

Hydrostatics: The study of pressurized liquids in equilibrium.

Pneumatic system: Fluid power systems that use compressed air as a working medium.

Pressure: The force per unit area exerted on a surface by a fluid.

TEST

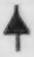
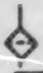
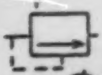
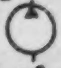
1. Advantages of fluid power systems do not include ...
   a. fast response due to high power-to-weight ratio.
   b. ease of control from remote locations.
   c. ruggedness and low maintenance requirements.
   d. force multiplication with low loss.
   e. ease of installation as compared to mechanical power transmission systems.
2. In a hydraulic power system, increasing the pressure at a fixed delivery rate will ...
   a. increase the operating speed.
   b. increase the maximum force produced.
   c. increase the system power.
   d. Both b and c are true.
   e. All of the above are true.
3. In a pneumatic power system, increasing the pressure at a fixed delivery rate will ...
   a. increase the operating speed.
   b. increase the maximum force produced.
   c. increase the system power.
   d. Both b and c are true.
   e. All of the above are true.
4. A piston 2 inches in diameter is operated at a pressure of 200 psig. The force produced is ...
   a. 628 lb.
   b. 400 lb.
   c. 2512 lb.
   d. 1628 lb.
   e. None of the above is correct.
5. A volume flow rate of 12 gal/min at a pressure of 200 psig produces how much power? (1 gal = 231 in^3)
   a. 9240 ft·lb/sec
   b. 412 ft·lb/sec
   c. 46,200 ft·lb/sec
   d. 0.71 hp
   e. 1.4 hp

6. A piston 2 inches in diameter moves 4 inches at an operating pressure of 200 psig. How much work is done?
   - a. 1672 ft·lb
   - b. 2512 ft·lb
   - c. 836 ft·lb
   - d. 209 ft·lb
   - e. 105 ft·lb

7. If a pipe carrying a moving fluid has a reduction in diameter...
   - a. the pressure increases.
   - b. the fluid velocity increases.
   - c. both pressure and fluid velocity increase.
   - d. the power of the system is reduced.
   - e. neither pressure nor velocity increases.

8. If the volume of a gas at a constant temperature is reduced to one-fourth of its original volume, the pressure will be ...
   - a. unchanged.
   - b. doubled.
   - c. four times as great.
   - d. halved.
   - e. eight times as great.

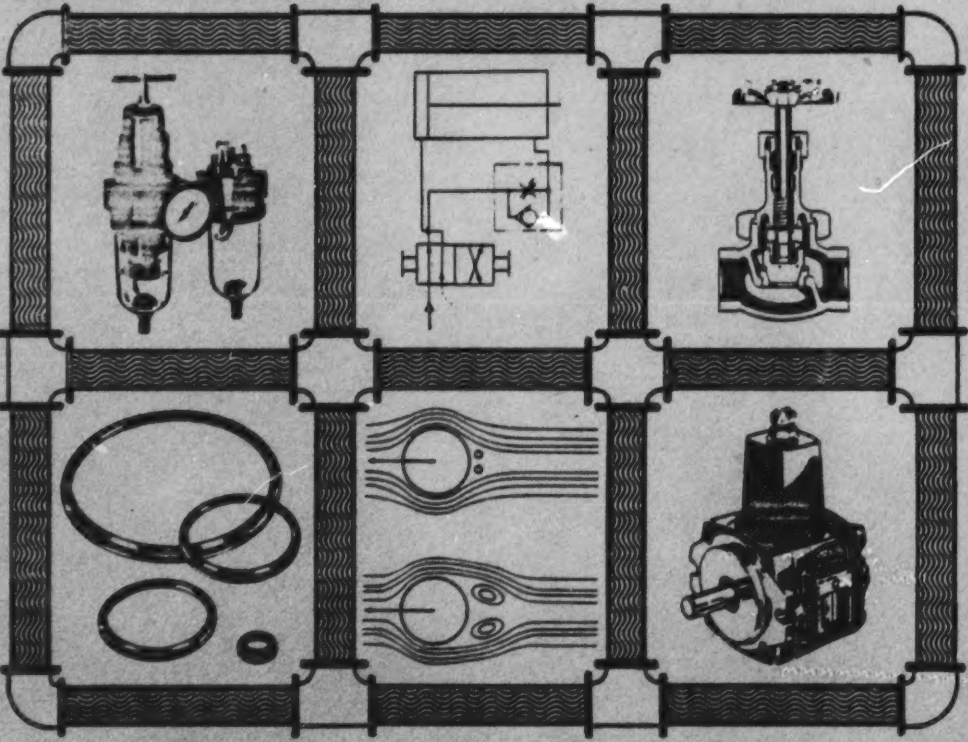
9. The continuity equation ...
   - a. may be applied to either gases or liquids.
   - b. states that the pressure of a liquid drops as the diameter of the pipe carrying it decreases.
   - c. implies lower fluid velocities in larger diameter sections of pipe.
   - d. applies only to systems in which the power transfer fluid is recirculated continuously.
   - e. None of the above are true.

10. Which of the following is an incorrect fluid power symbol?
   - a.  direction of flow in pneumatic line
   - b.  filter
   - c.  pressure relief valve
   - d.  pump
   - e. All of the above are correct.

ENERGY TECHNOLOGY

CONSERVATION AND USE

FLUID POWER



MODULE FL-02

FLUID POWER PROPERTIES AND CHARACTERISTICS

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

The most important material in any fluid power system is the working fluid. In hydraulic power systems, the working fluid is an incompressible liquid — usually petroleum oils. In pneumatic power systems, the only working fluid is compressed air.

This module discusses the characteristics and types of hydraulic fluids, as well as procedures for maintaining and replacing hydraulic oils. Advantages and disadvantages of pneumatic fluids are also discussed.

In the laboratory, the student will construct and operate hydraulic and pneumatic circuits that power double-acting cylinders and compare cylinder operation of the two systems.

PREREQUISITES

The student should have completed Module FL-01, "Introduction and Fundamentals of Fluid Power."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the following terms as they apply to hydraulic fluids:
    a. Viscosity
    b. Viscosity index
    c. Pour point
    d. Lubricating ability
    e. Film strength
    f. Demulsibility
    g. Flash point
    h. Fire point
    i. Specific gravity
2. Explain the difference between rust and corrosion and the cause of each in a hydraulic system.

3. List four undesirable consequences of using an oil with a viscosity that is too high, and list three undesirable consequences of using an oil with a viscosity that is too low.
4. Explain the problems that arise when a hydraulic oil oxidizes and the factors that cause rapid oil oxidation.
5. List 10 characteristics of a good hydraulic oil.
6. Describe the desirable and undesirable characteristics of the following types of hydraulic fluids:
   a. Water-oil emulsions
   b. Water-glycol solutions
   c. Synthetic fluids
7. List 10 precautions in the maintenance, handling, and storage of hydraulic oils.
8. Explain the steps necessary in replacing hydraulic oil in a system.
9. List five advantages and disadvantages of compressed air as a fluid power working medium, as compared to hydraulic oil.
10. Construct fluid power circuits for the operation of hydraulic and pneumatic double-acting cylinders. Compare the characteristics of the extension and retraction strokes for each cylinder and compare the operation of the two cylinders.

PROPERTIES OF HYDRAULIC FLUIDS

A variety of fluids — with different combinations of properties — is available for use in hydraulic power systems. A good hydraulic fluid must transmit fluid power with minimum losses, act as a lubricant for system components, and act as a sealant in the system, as well as prevent rust, corrosion, and deterioration of components. Selection of the proper fluid for the application and components involved has a considerable effect on system performance, maintenance, cost, and service life. The following paragraphs discuss properties that should be considered when selecting the proper fluid for a hydraulic power system.

VISCOSITY

Viscosity is a measure of the fluid's internal resistance to flow or shear forces at a specific temperature and pressure. Figure 1 shows two parallel plates separated by a film of fluid. The bottom plate is stationary, and the top plate is being moved by the application of a shear force. The liquid in contact with each plate remains virtually at rest with respect to the plate. Therefore, the lowest layer of fluid in the figure is stationary (zero velocity). The upper layer has the velocity of the moving plate and, thus, moves with it. Layers of fluid between the two plates slide past one another with the velocity profile shown.

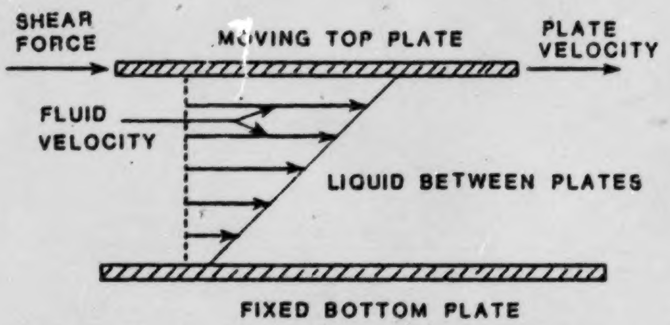


Figure 1. Fluid Velocity Profile Between Parallel Plates due to Viscosity.

The absolute or dynamic viscosity of the fluid is the ratio of the applied shear force to the velocity of the fluid. If the fluid has a low viscosity, resistance to motion is low and the upper plate moves easily. If the fluid has a high viscosity, resistance is high and greater force is required to move the upper plate.

Viscosity also affects the flow rate of a fluid through a pipe with a given pressure drop. Low viscosity fluids flow easily at higher rates with little power loss. High viscosity fluids flow more slowly and produce more power losses. Thus, lower viscosity fluids are desirable for increasing the efficiency with which fluid power is transmitted through conducting pipes. However, this does not mean that lower viscosity fluids are always the best choice — lower viscosity generally is accompanied by reduced lubricating and sealing ability.

Figure 2 shows a Saybolt Universal Viscosimeter used for testing the viscosity of petroleum products. This instrument does not measure dynamic viscosity but gives an indication of relative viscosities on an arbitrary scale. Sixty milliliters of the fluid to be tested are placed in the inner cylinder. Another fluid surrounding this cylinder is used to maintain the proper test temperature. The cork is removed, and the time required for the test fluid to run out through a calibrated outlet tube is measured. This time (in seconds), called the Saybolt Universal Seconds (SUS), is often specified for hydraulic oils. Most hydraulic oils have viscosities in the range of 135 to 315 SUS at 100°F; however, oils with higher or lower viscosities are sometimes used.

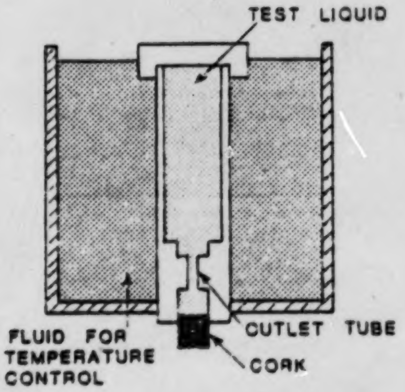


Figure 2. Saybolt Universal Viscosimeter.

The Society of Automotive Engineers (SAE) has established standardized numbers for indicating the viscosities of automotive oils. Table 1 compares SAE numbers to the viscosity in SUS at two temperatures. The designation "W" indicates an oil having a viscosity that changes more slowly as temperature increases. Typical hydraulic oils have viscosities in the same range as higher grade motor oils.

TABLE 1. COMPARISON OF SAE AND SUS OIL RATINGS.

SAE Number	Saybolt Universal Seconds	
	(at 100°F)	(at 210°F)
10 W	202	48
20 W	323	57
30	538	68
40	850	84
50	1174	100

If the viscosity of the fluid is too high for the system in which it is used, the following undesirable conditions may result:

1. High resistance to fluid flow may cause sluggish operation of various components or pump cavitation.
2. Efficiency may drop due to increased power consumption to overcome friction losses.
3. Fluid temperature may increase because of high friction.
4. Pressure drop along conductors may be higher than desired, resulting in a decrease in pressure available for useful work.

If the viscosity of the fluid is too low, the following undesirable conditions may result:

1. Excessive leakage may occur in clearance spaces in valves and driven components.
2. Pump leakage may occur, resulting in reduced pump delivery, pressure, and efficiency.
3. An increase in wear may occur because of reduced strength and thickness of the lubricating film between moving parts.

Since the pump is the most critical hydraulic component with respect to viscosity, the viscosity recommendations of the pump manufacturer are used for fluid selection. Other components of the system are chosen that are compatible with the pump.

VISCOSITY INDEX

Ideally, the viscosity of a hydraulic fluid should either remain constant or change very little as the fluid temperature changes. However, this is not the case for most hydraulic fluids. The viscosity index is an indication of the relative change in viscosity as temperature changes. Viscosity index is measured on an arbitrary scale: a specific paraffin-base oil with a small viscosity change is assigned a value of 100, and a specific asphalt-base oil with a large viscosity change is assigned a zero value. Thus, higher values of viscosity index indicate less change in viscosity as temperature changes. It also indicates a more desirable hydraulic fluid. Since the viscosity index is based on an arbitrary scale, some oils have a value of less than zero. These oils are generally unsuitable for hydraulic power applications. Chemical additives are included in some oils to raise the viscosity index to as high as 170.

As the temperature is decreased, the oil thickens until it will no longer flow. The pour point is the lowest temperature at which the fluid will flow, usually 5°F above the temperature at which no flow occurs. The lowest operating temperature of a hydraulic system should be 20°F above the pour point of the oil.

LUBRICATING ABILITY

Wear is the actual removal of surface material due to frictional forces between moving surfaces in contact. The amount of wear depends upon the finish and hardness of the surfaces and the magnitude of the forces holding the surfaces in contact. Metal surfaces that are stationary with respect to one another and subjected to large forces form microwelds that bond the two surfaces together. Moving these surfaces later breaks these tiny welds and roughens the surfaces, thereby increasing the wear rate.

The lubricating ability of an oil, also called lubricity or oilness, is the ability of an oil to reduce friction and wear. Lubricating ability is dependent in part upon the viscosity of the oil, but chemical properties are equally, if not more, important. The film strength of an oil — which is directly related to its viscosity — is the ability of the oil to maintain an oil film between moving parts in order to prevent direct metal-to-metal contact. Higher film strength reduces wear, but it is generally accompanied by higher viscosity. Adequate film strength is important in hydraulic systems in protecting pump components.

Chemical additives are often used to increase the lubricating ability of oils. These additives are usually organic compounds that prevent the microwelding of surfaces under pressure. They may plate out on the surfaces, forming a surface layer that adheres strongly to the surface. Two such surface layers will slide past each other more easily — and, therefore, with less damage — than unprotected metal. Other compounds chemically react with metal surfaces to prevent the formation of microwelds under high pressure. This prevents seizure and the increased roughness resulting from breaking the seizure.

Lubricating ability and film strength are not determinable by oil specifications. They are usually indicated by relative terms such as "poor," "good," or "excellent."

RUST AND CORROSION PREVENTION

Rust and corrosion are two different chemical processes that can damage or destroy hydraulic components. Rust is the chemical reaction between oxygen and iron or steel surfaces. The oxygen necessary for the process is usually provided by the presence of moisture in the system. Moisture may enter the hydraulic fluid in the form of atmospheric moisture in contact with the oil surface in the reservoir or through leaks in the system that allow either air, condensation, or cooling water to enter the system. The moisture is partially dissolved in the hydraulic fluid and may also be carried with the fluid in the form of small droplets. These conditions promote rust, particularly when a system is inactive for a long period of time after operation at an elevated temperature.

Corrosion is the chemical reaction between metal surfaces and acids. Many hydraulic fluids contain small amounts of acid. Furthermore, the breakdown of the oil — as it ages during use — increases its acid content. The neutralization number, which is an indication of the acid content of a hydraulic fluid, indicates the number of milligrams of potassium hydroxide needed to neutralize the acid in one gram of fluid. The neutralization number usually is not an important consideration in selecting an oil, but it is useful in determining when an oil has deteriorated and should be replaced.

Many oils contain chemical additives that plate out on metal surfaces to form a protective layer, thereby reducing both rust and corrosion.

OXIDATION STABILITY

Although properly refined petroleum oils are inherently resistant to deterioration, oxidation of the oil can — and does — take place. Excessive oxidation results in the following:

- Increase in oil viscosity
- Deposits of gummy oxidation products on pumps, motors, and valves
- Formation of heavy sludge that settles in low points in the system
- Formation of acids that corrode metal parts

Oil oxidation occurs primarily because of air in contact with the oil in the reservoir. This air is absorbed into the oil to a slight degree. Air bubbles that enter the system — either from foam in the reservoir or from air leaks in the suction line or seals — are compressed by the high pressure at other points in the system. This high pressure air promotes oil oxidation. The oxidation process increases at increased temperature. It is estimated that the useful life of a typical hydraulic oil is decreased by 50% for each 15-degree rise in temperature above 140°F. Heavier oils generally resist oxidation better than lighter oils. The temperature of the oil in the reservoir is not necessarily a good indication of operating temperatures. Localized hot spots occur because of higher pressures and slight compression of the oil at the gear teeth, at bearings, and at points where the oil flows through a small orifice under high pressure. Increased temperatures at these points, particularly in the presence of entrained air, may cause rapid decomposition of hydraulic oils.

The rate of oxidation is increased by the presence of foreign matter in the oil. Dirt, small particles of metal from worn components, and sludge from earlier oxidation tend to promote increased oxidation. Thus, maintenance of oil in a clean condition is essential to extended oil life. As an oil ages, it becomes darker in color and higher in both viscosity and neutralization number. These characteristics may be used to determine when the fluid should be replaced. Many oils contain chemical additives to inhibit oxidation.

DEMULSIBILITY

Demulsibility, the property of a hydraulic fluid that enables it to separate rapidly and completely from moisture, is important because most hydraulic systems are susceptible to the presence of moisture in the system and because of the damaging properties of such moisture. Most petroleum-base oils have good demulsibility and maintain it well during the useful life of the oil. However, in some oils, demulsibility decreases as the oil ages and as oxidation occurs. This generally results in greater water content, reduced lubricant and sealant characteristics, and reduced life of the oil and system components.

RESISTANCE TO FOAMING

As discussed previously, the presence of air bubbles in an oil increases the oil oxidation rate. Foam may be formed when oil is returned to the reservoir by a pipe that does not extend below the reservoir oil level or when the pressure is reduced on high pressure fluid containing dissolved air. The defoaming characteristic of oil is an indication of how rapidly such bubbles rise to the oil surface and burst. Low viscosity oils are more resistant to foaming than high viscosity oils. Chemicals are often added to oils to increase the rate at which air bubbles burst, thereby reducing foam levels.

Foaming problems can also be greatly reduced by proper design of the oil reservoir and maintenance of the proper oil level. Serious damage may result if a leak reduces the oil level in the reservoir to the point that air is sucked into the pump intake.

FLASH AND FIRE POINTS

Fire hazards are an important consideration in many hydraulic power applications. Flash point is the temperature at which oil gives off sufficient vapors to ignite momentarily, but not enough to sustain a flame. The fire point is the temperature at which vapors are given off at a rate sufficient to sustain continuous combustion.

SPECIFIC GRAVITY

The specific weight is the weight per unit volume of the fluid. Water, for example, weighs 62.4 pounds per cubic foot. The specific gravity of a fluid is the ratio of the specific weight of the fluid to the specific weight of water. If the specific gravity of a liquid is 1.2, then its specific weight is (1.2 x 62.4 lb/ft^3) or 74.9 lb/ft^3. Commercially available hydraulic fluids have specific gravities in the range of 0.80 to 1.45. The specific gravity is usually of little importance in selecting a fluid.

TYPES OF HYDRAULIC FLUIDS

Several fluids can be used in hydraulic power systems. This section discusses characteristics and applications of common hydraulic fluids.

WATER

Water is sometimes used as a working fluid in systems requiring a large volume of fluid, such as elevators and large forging presses. Water is inexpensive and nonflammable; however, the range of operating temperatures, poor lubricating properties, and promotion of rust limit its use in many hydraulic power systems.

PETROLEUM OILS

A properly refined and treated petroleum oil is the best fluid for most hydraulic power applications. A wide variety of petroleum oils is available. However, three types of petroleum oils are most commonly used: Pennyslvania, or paraffin-base oils; Gulf Coast, or naphthenic-base or asphalt-base oils; and Mid-Continent, or mixed-base oils containing a mixture of naphthenic and paraffin compounds. The operating properties of these oils are improved by the addition of several chemical compounds. These compounds increase the viscosity index, inhibit oil oxidation, reduce foaming, increase film strength and lubricating ability, reduce rust and corrosion, and prevent the formation of sludge and gum in the system. Additives are included in the processing of oils and should not be added by the user.

A good hydraulic oil should include the following properties:

- Correct viscosity to provide fluid power transfer without excessive friction losses and to seal working parts
- High viscosity index to reduce changes in viscosity as temperature changes.
- Good lubricating ability to prevent wear to working parts
- Prevention of rust and corrosion of metal parts

- Chemical stability to resist oil oxidation
- Resistance to foaming
- Good demulsibility to remove water from the oil
- Resistance to precipitating sludge and gum on working parts
- Compatibility with seal materials
- Long service life

Petroleum oils are available with all of the properties listed above. The only serious disadvantage of petroleum oils is that they will burn and, thus, present fire hazards in some applications. Several types of fluids have been developed for applications in which the fire hazards of petroleum oils are unacceptable.

The fire resistance of the working fluid is particularly important in processing equipment for hot metals, coal mining applications, and aircraft and marine fluid power systems.

WATER-OIL EMULSIONS

Water-oil emulsions are fluids consisting of about 40% water completely dispersed in 60% special petroleum oil with a soluble-oil type emulsifying agent added. They afford good fire protection because the steam released when the fluid strikes a hot surface blankets the surface and prevents oxygen from reaching the oil vapors. The water in the fluid gives good heat transfer properties but also promotes rust and corrosion. Thus, large quantities of corrosion inhibitors are required. The lubricating properties are fair but not as good as that of pure oil. The operating temperatures of water-oil emulsions range from -20°F to 175°F. They are compatible with most seal materials except natural rubber. Fluid maintenance is important because the water evaporates during use and must be replenished.

WATER-GLYCOL FLUIDS

Water-glycol fluids consist of a solution of 40% water and 60% glycol with a variety of additives. Their fire resistance is excellent if the water content is maintained. The viscosity index is high, but the viscosity increases if the water content is reduced by evaporation. Corrosion resistance is fair, except when used with radial piston pumps where rusting is usually a problem and with exposure to zinc or cadmium metal. Wear resistance is good at lower pressures; at high pressures, gear-type and piston-type pumps often show excessive wear. The high density of these fluids can also result in pump starvation. The operating temperature range of these fluids is approximately -10°F to 180°F. Water-glycol fluids are compatible with most seal materials, but special paints must be used wherever they may come in contact with these fluids.

SYNTHETIC FLUIDS

Synthetic fluids give the highest fire resistance temperatures. Several types are available, including phosphate esters, chlorinated hydrocarbons, mixtures of the two, and several other chemical compounds. Synthetic fluids are stable in operation up to about 300°F. These fluids have good lubricating properties but do not offer protection against rust and corrosion and require large quantities of additivies. Disadvantages of synthetic fluids include a low viscosity index and incompatibility with many seals and other materials. In particular, the phosphate esters readily dissolve paints, pipe thread compounds, most seal materials, and most electrical insulation. Samples of seal materials should be tested for compatibility before synthetic fluids are used in a system.

Table 2 lists the recommended packing materials for use with fire-resistant hydraulic fluids.

TABLE 2. RECOMMENDED PACKING MATERIALS FOR FIRE-RESISTANT FLUIDS.

Fluid	Packing Material
Water-oil emulsions	Nitrile rubber (NBR, Buna-N, Hycar) (packing should be selected by testing various rubber materials). Braid impregnated with Teflon suspensoid.
Water-glycol	Natural rubber. Leather (treated for water resistance).
Phosphate ester	Butyl rubber. Silicon rubber. Leather impregnated with Thiadol. Byram. Braid with soap-glycerine lubricant which will not wash out. Braid lubricated by impregnation with Teflon suspensoid.

Table 2. Continued.

Silicate esters	Nitrile rubber. Chloroprene rubber. Polyacrylate rubber. Leather impregnated with Thiokol. Braid impregnated with Teflon suspensoid.
Silicon base	Nitrile rubber. Byram. 1F4 Rubber (formerly Poly FBA). Braid impregnated with Teflon suspensoid.

MAINTENANCE OF HYDRAULIC OILS

All hydraulic fluids require proper maintenance and handling both in the system and during storage. Fire-resistant fluids usually have special requirements that are dependent upon the fluid type. Because most hydraulic power systems use petroleum oils, this section lists general precautions in the maintenance, handling, and storage of hydraulic oils:

1. Store oil in a clean container. The container should be free of dirt, lint, used oil, or oil of any other type.
2. Keep lids or covers tight on all oil containers to prevent dirt and dust from settling on the oil surface and to prevent contamination by water.
3. Store oil in a dry location. Oil containers should never be exposed to rain, snow, or other sources of water.
4. Use clean containers for transferring oil from storage to the tank or reservoir. Always clean transfer containers before and after each use.
5. Select an oil that is compatible with the pump specifications. Pumps are the most critical system component when selecting a hydraulic oil.
6. Never mix different types or grades of hydraulic oil. Oils having different properties are often incompatible with one another and may result in system damage.
7. Make sure the entire system is clean before changing the oil in the hydraulic power unit. Do not add clean oil to dirty oil.
8. Check the oil level and quality in the hydraulic power unit regularly. Have the oil supplier check samples of used oil to identify any problems or contaminants in the system.
9. Drain all oil from the system and replace it at regular intervals. The useful lifetime of a hydraulic oil depends on the quality of the oil and the operating conditions. Some systems operate satisfactorily for as long

as two years without an oil change. Others require fluid changes as often as once a month. Most systems fall somewhere between these two extremes. The oil change schedule for a particular system should be established after testing of the oil during initial system operation.

10. Dispose of used oil properly, and do not return used oil to the system.

REPLACING HYDRAULIC OIL

The general procedure for replacing hydraulic oil is as follows:

1. Drain all oil from the system, by disconnecting and draining piping and components, or force oil out with clean, dry air under pressure.
2. Inspect and clean filters and oil reservoir.
3. Fill system with a recommended flushing agent and operate for a period of time.
4. Drain flushing agent from system, inlcuding lines and components.
5. Replace filters (if necessary) and refill system with new oil.

Several procedures may be used for flushing the system. Since it is virtually impossible to remove all the flushing agent from the system, materials that might be damaging to either system components or the fresh charge of oil should not be used. Kerosene, naphtha, alcohol, steam, or water should never be used for flushing the system. In addition, the flushing agent should be compatible with all seals in the system. Carbon tetrachloride should never be used because it reacts with water to form hydrochloric acid, which can result in serious corrosion problems.

One procedure that is sometimes used to flush a system is to fill the system with a lightweight oil and operate the system for a few hours without load, possibly at an elevated temperature. This flushing method requires that the pump operate for an extended period with an oil of lower viscosity than that for which it is designed. This can result in excessive wear and pump damage. Therefore, this method should not be used without consulting the pump manufacturer.

A safer method is to fill the system with the operating oil as a flushing agent and to drain and refill the system after a few hours of operation. This method will remove many system contaminants but may not remove sludge and gum that are not highly soluble in the oil.

The preferred method is to use a special purging oil that contains solvents for removing deposits from the system.

If the working fluid in a system is to be changed from a petroleum oil to a fire-resistant fluid, or vice versa, special precautions must be followed to remove all old fluid. In this case, the system should be completely dismantled and cleaned thoroughly. Steam cleaning of components and piping is recommended. All seals should be checked for compatibility with the new fluid, and paints and sealers should be checked for resistance to any of the fire-resistant fluids.

In all maintenance procedures and during system operation, the removal of spilled or leaking fluid is essential. Spilled fluids collect dirt and present safety and fire hazards.

PROPERTIES OF PNEUMATIC FLUIDS

The only gas widely used in pneumatic power systems is compressed air. Other gases may be used, but their application is so rare that they will not be discussed.

Pneumatic and hydraulic systems usually do not compete for the same applications since the characteristics of the two system types are considerably different. Table 3 lists advantages and disadvantages of compressed air as compared to oil as a working fluid.

TABLE 3. ADVANTAGES AND DISADVANTAGES OF COMPRESSED AIR AS A WORKING FLUID.

Advantages	Disadvantages
• Air will not burn and may be used in applications where a combustible fluid would present fire hazards.	• Due to its compressibility, air cannot be used in applications where accurate positioning or rigid holding is required.
• Air can be used in applications where hot spots cause elevated fluid temperatures.	• Because air is compressible, large cylinders producing large forces tend to be sluggish.
• Because of its compressibility, air can produce more rapid motion than liquid fluids.	• Pneumatic systems are far less efficient in power transmission than hydraulic systems.
• Air is not messy.	• Air always contains dirt, dust, and water vapor that must be removed before the air can be used in a pneumatic power system.
• Air is readily available from the atmosphere at no cost.	• Air has very poor lubricating ability.
• Air can be exhausted directly back into the atmosphere, eliminating the need for return piping.	

Module FL-03, "Fluid Storage, Conditioning and Maintenance," discusses the preparation necessary before compressed air can be used as the working medium in a fluid power system.

SUMMARY

The most important material in a hydraulic power system is the working fluid. This fluid transmits fluid power, acts as a lubricant and sealant in the system, and prevents rust and corrosion of system components. The most commonly used hydraulic fluid is petroleum oil. Its major disadvantage is that it burns. Several other fluids may be used when a fire-resistant fluid is desirable. The most important property of any hydraulic fluid is its viscosity. Viscosity is an indication of the internal resistance of the fluid to flow. Fluid pumps are designed to operate with liquids of a specific viscosity. Other system components, including the hydraulic fluid, are chosen that are compatible with pump requirements. Using a fluid of the wrong viscosity may damage the pump. Hydraulic fluids should always be maintained in a clean condition and checked regularly and replaced when they fall below minimum system requirements.

The only fluid commonly used in pneumatic power systems is compressed air. The behavior of pneumatic systems differs from hydraulic systems because the working fluid is a compressible gas.

EXERCISES

1. List and explain the advantages and disadvantages of compressed air as a working fluid for fluid power systems, as compared to hydraulic oil. List five examples of the use of each type of fluid. Consult a library.
2. Explain the consequences of using a hydraulic oil of incorrect viscosity.
3. Discuss the problems of using a hydraulic oil with a low viscosity index.
4. Discuss the problems involved in the use of the following types of hydraulic fluids:
   a. Water
   b. Petroleum oils
   c. Water-oil emulsions

    d. Water-glycol solutions
    e. Synthetic fluids

5. Explain factors contributing to the oxidation of petroleum oils in hydraulic systems and the problems that result from oil oxidation.
6. Explain the difference between rust and corrosion and the causes of each in a hydraulic system. Explain how each may be reduced.
7. List and explain the precautions necessary in the handling, storage, and maintenance of hydraulic oils.
8. Explain the procedures and materials that can be used in flushing a hydraulic system. Explain the dangers in using solvents and oils of low viscosity to flush hydraulic systems.
9. List the four basic functions that must be performed by a good hydraulic oil and the 10 characteristics of a good oil.

LABORATORY MATERIALS

Hydraulic power unit with pressure meter and internal pressure relief valve
Hydraulic pressure relief valve
Hydraulic check valve
Hydraulic flowmeter
Hydraulic directional control valve
Double-acting hydraulic cylinder (piston diameter and rod diameter known)
Connecting hydraulic hoses
Cylinder loading device
Pneumatic power unit with FRL
Pneumatic flowmeter
Pneumatic directional control valve
Double-acting pneumatic cylinder
Connecting pneumatic hoses
Stopwatch

LABORATORY PROCEDURES

LABORATORY 1. HYDRAULIC EXPERIMENT.

In this laboratory, the student will construct fluid power circuits for the operation of double-acting hydraulic and pneumatic cylinders and evaluate cylinder operation on the extension and retraction strokes.

1. Record the pressure setting to be used on the pressure relief valve (maximum pressure), the piston diameter, and the rod diameter in Data Table 1.
2. Calculate the area of the piston and the area of the piston minus the area of the rod. Record these figures in Data Table 1. The first area is the effective area for the extension stroke; the second is for the retraction stroke.
3. Multiply the pressure times each area to obtain the maximum forces produced by the cylinder for each stroke. Record force values in Data Table 1.
4. Construct the circuit in Figure 3. Set the pressure relief valve for the desired pressure.
5. Have instructor check circuit before operation.
6. Turn on the hydraulic power unit and actuate the DCV without tension on the loading device. Operate the cylinder in both directions several times to remove trapped air from the system. Observe the speed of piston motion in both directions.
7. Increase the tension on the cylinder loading device to the point where the retraction force is just capable of retracting the piston.
8. With the piston fully retracted, position the DCV to extend the piston. Measure and record the following quantities:
    a. Measured pressure
    b. Flow rate

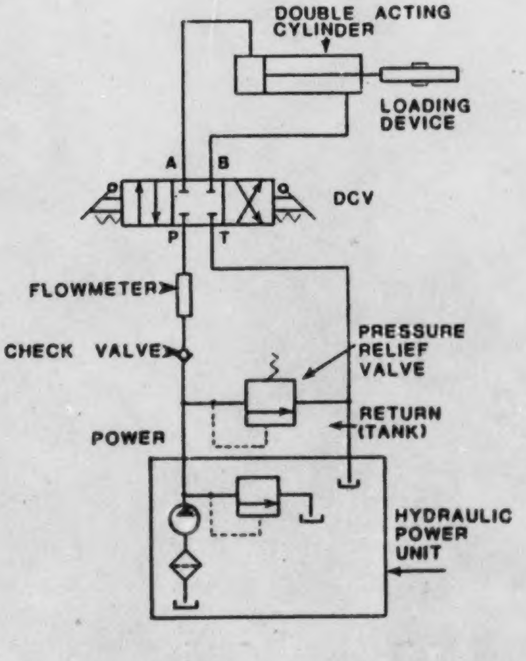


Figure 3. Hydraulic Experimental Circuit.

   c. Time for extension stroke

9. With the piston fully extended, position the DCV to retract the cylinder. Measure and record the following quantities:
   a. Pressure
   b. Flow rate
   c. Time for retraction stroke
10. For each stroke, calculate the force produced by multiplying the measured pressure times the effective area and record in Data Table 1.
11. For each stroke, calculate the power by multiplying the flow rate (1 gal = 231 in^3) times the pressure. Convert the result to foot-pounds per second and record in Data Table 1.
12. For each stroke, calculate the total energy expended by multiplying power times the time required. Record the result in Data Table 1.
13. Increase the tension on the loading device and operate the cylinder in both directions until the cylinder will no longer move.
14. In the discussion portion of Data Table 1, discuss the differences in maximum force available and operating time for a double-acting hydraulic cylinder during the extension and retraction strokes. Include the reason for these differences.
15. Turn off the hydraulic power unit. Clean and store all hydraulic components.

LABORATORY 2. PNEUMATIC EXPERIMENT.

1. Following the same procedures outlined in Steps 1-3 of the hydraulic experiment, complete the calculation portion of Data Table 2 for the pneumatic experiment.
2. Construct the circuit shown in Figure 4. Set the regulator for the desired pressure. Have instructor check circuit before operation.
3. Follow the same procedure outlined in Steps 6-15 of the hydraulic experiment and complete Data Table 2 for the pneumatic experiment.

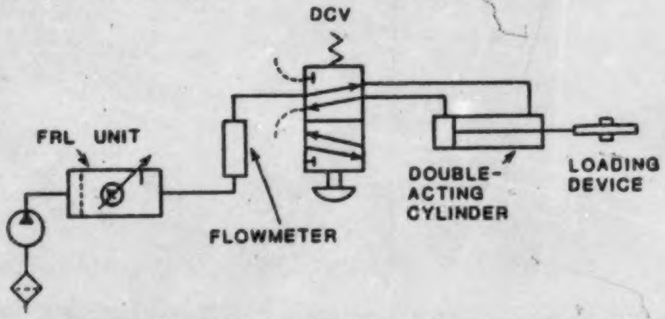


Figure 4. Pneumatic Experimental Circuit.

4. Write a report summarizing the results of this experiment and comparing the action of double-acting hydraulic and pneumatic cylinders.

DATA TABLES

DATA TABLE 1. HYDRAULIC EXPERIMENT.

Calculations:

Maximum pressure: ______________________________

Piston diameter: ______________________________

Rod diameter: ______________________________

Area of piston (extension stroke area): ________________

Area of piston minus area of rod
(retraction stroke area): ______________________

Maximum extension force: ______________________

Maximum retraction force: ______________________

Experimental:

Measured pressure for extension stroke: ________________

Flow rate of extension stroke: ____________________

Time for extension stroke: ______________________

Force of extension stroke: ______________________

Power for extension stroke: ______________________

Energy of extension stroke: ______________________

Measured pressure for retraction stroke: ______________

Flow rate for retraction stroke: __________________

Time for retraction stroke: ______________________

Force of retraction stroke: ______________________

Power for retraction stroke: ______________________

Energy of retraction stroke: ______________________

Discussion:

DATA TABLE 2. PNEUMATIC EXPERIMENT.

Calculations:

Maximum pressure: ____________________

Piston diameter: ____________________

Rod diameter: ____________________

Area of piston (extension stroke area): ____________________

Area of piston minus area of rod
(retraction stroke area): ____________________

Maximum extension force: ____________________

Maximum retraction force: ____________________

Experimental:

Measured pressure for extension stroke: ____________________

Flow rate for extension stroke: ____________________

Time for extension stroke: ____________________

Force of extension stroke: ____________________

Power for extension stroke: ____________________

Enegy of extension stroke: ____________________

Measured pressure for retraction stroke: ____________________

Flow rate for retraction stroke: ____________________

Time for retraction stroke: ____________________

Force of retraction stroke: ____________________

Power for retraction stroke: ____________________

Energy of retraction stroke: ____________________

Discussion:

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GLOSSARY

Corrosion: The chemical reaction between metals and acids.

Demulsibility: The ability of a hydraulic oil to separate from entrained or dissolved moisture.

Fire point: The temperature at which an oil will give off sufficient vapor to sustain combustion.

Film strength: The ability of a fluid to maintain a film between moving parts under pressure.

Flash point: The temperature at which an oil will give off sufficient vapor to ignite momentarily, but not enough to sustain a flane.

Lubricating ability: The ability of a fluid to reduce friction between moving parts and, thus, wear of the parts.

Pour point: The lowest temperature at which a fluid will flow, usually 5°F above the temperature at which no flow will occur.

Rust: Oxidation of iron or steel.

Specific gravity: The ratio of weight per unit volume of a liquid to the weight per unit volume of water.

Viscosity: A measure of a fluid's internal resistance to flow or shear forces. High viscosity indicates high internal resistance.

Viscosity index: An indication of the relative change in viscosity of a fluid as its temperature changes. A high viscosity index indicates less change in viscosity as temperature changes.

1. Which of the following is not an essential requirement of a hydraulic oil?
   a. Prevent rust and corrosion of working parts in the system.
   b. Transmit fluid power with minimum losses.
   c. Maintain viscosity as temperature changes.
   d. Act as a sealant for system components.
   e. Lubricate moving parts of the system.
2. When considering the viscosity of the oil to be used in a hydraulic system, the most important consideration is ...
   a. choosing an oil of the lowest possible viscosity to reduce fluid friction in piping.
   b. choosing an oil of high viscosity to reduce system leaks.
   c. choosing an oil that is compatible with pump specifications.
   d. choosing an oil that is compatible with cylinder operation.
   e. Both a and c are equally important.
3. An oil with a viscosity index of 100 indicates ...
   a. it has the highest possible viscosity index.
   b. its viscosity changes greatly as temperature changes.
   c. its viscosity does not change as temperature changes.
   d. it should be used only under constant temperature conditions.
   e. None of the above are true.
4. When a hydraulic oil oxidizes, which of the following occurs?
   a. Its viscosity decreases.
   b. It promotes rust due to increased acid content.
   c. It deposits sludge in low points in the system.
   d. Its viscosity index falls sharply.
   e. Both b and c are true.
5. Oil oxidation is promoted by ...
   a. entrained air bubbles.
   b. high temperature operation or hot spots.
   c. contaminants in the oil.
   d. All of the above.
   e. Only a and b are true.

6. Which of the following is the least important characteristic to consider in selecting a hydraulic oil?
   a. Viscosity
   b. Viscosity index
   c. Lubricating ability
   d. Specific gravity
   e. Oxidation stability

7. Which of the following hydraulic fluids is most likely to cause problems with seal materials?
   a. Petroleum oils
   b. Water-glycol fluids
   c. Water-oil emulsions
   d. Water
   e. Phosphate esters

8. Which of the following hydraulic fluids has the greatest fire resistance?
   a. Phosphate esters
   b. Water-oil emulsions
   c. Water-glycol solutions
   d. Petroleum oils
   e. Compressed air

9. Which of the following procedures is acceptable in flushing most hydraulic systems when changing oil?
   a. Use a very lightweight oil and operate the system under load.
   b. Flush the entire system with kerosene.
   c. Use the normal operating oil for flushing the system and operate without load for several hours.
   d. If in doubt, add fresh oil without flushing the system. This is always the safest thing to do.
   e. Either a or c is correct.

10. Which of the following is not an advantage of pneumatic power systems as compared to hydraulic systems?
   a. Air will not burn.
   b. Air can be taken from the atmosphere and exhausted back into the atmosphere.
   c. Pneumatic systems are cleaner and less susceptible to contamination since the air does not recirculate and carry contamination with it.

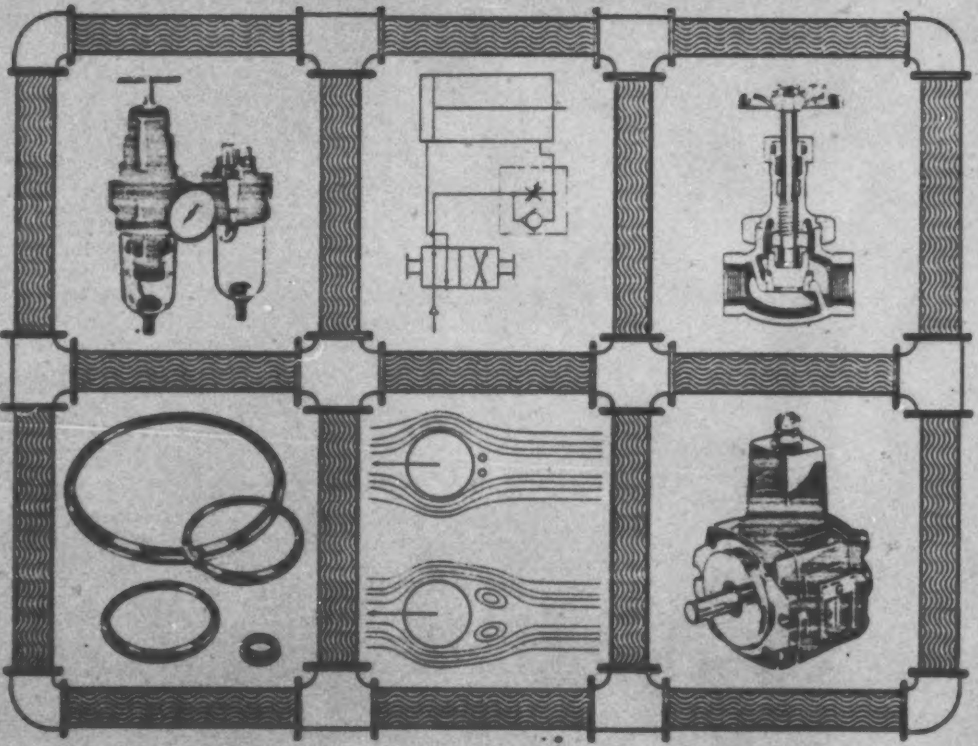
d. Compressed air as a working fluid results in more rapid operation of large cylinders producing very large forces.

e. Neither c nor d is an advantage of pneumatic systems.

ENERGY TECHNOLOGY

CONSERVATION AND USE

FLUID POWER



MODULE FL-03

FLUID STORAGE, CONDITIONING, AND MAINTENANCE

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

The most important material in any fluid power system is the fluid itself. Proper operation and extended life of fluid power components is dependent upon maintenance of the fluid in the proper condition for operating the system while protecting system components. The components most susceptible to damage because of contamination in the fluid are the seals of the working components.

This module discusses the types of seals used in hydraulic and pneumatic systems and fluid conditioning methods used to maintain cleanliness of the working fluids and, thus, protect the seals. The discussion includes design and functions of hydraulic fluid reservoirs and compressed air tanks; construction and functioning of hydraulic filters; components used for filtering, pressure regulation, and lubrication in pneumatic systems; and construction and materials used in all common seals.

In the laboratory, the student will disassemble and reassemble a variety of fluid power components used in fluid maintenance and a variety of fluid power seals. Components included are hydraulic filters, pneumatic filter-regulator-lubricator units, and several types of seals used in pneumatic and hydraulic cylinders.

PREREQUISITES

The student should have completed Module FL-02, "Fluid Properties and Characteristics."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. List seven characteristics of a good hydraulic reservoir.
2. Sketch a hydraulic reservoir and explain its construction and the function of each major part.
3. Explain the role of the compressed air tank in fluid conditioning in a pneumatic system.

4. Explain the importance of controlling the temperature of the fluid in hydraulic and pneumatic systems and how this is accomplished in each system type.
5. Explain the operation of the following types of hydraulic filters:
   a. Mechanical filter
   b. Absorbent filter
   c. Adsorbent filter
6. Explain the advantages and disadvantages of the following hydraulic filter locations:
   a. Suction line filter
   b. High-pressure line filter
   c. Return line filter
   d. Bypass filter
7. Explain, with the use of diagrams, the operation of each of the elements in a pneumatic filter-regulator-lubricator unit.
8. Draw diagrams of each of the following types of seals, and list the applications and characteristics of each:
   a. Compression seals
   b. O-rings
   c. V-rings
   d. Piston cup packings
   e. Piston rings
   f. Wiper rings
9. List the characteristics, applications, and approximate operating temperature ranges of the following seal materials:
   a. Leather
   b. Buna-N
   c. Buna-S
   d. Viton
   e. Neoprene
   f. Silicone rubber
   g. Teflon
10. In the laboratory, disassemble and reassemble the following fluid power components. Make a sketch of each and discuss its condition and operation.
    a. Sump strainer
    b. Line filter

c. FRL unit
d. Hydraulic reservoir
e. Compression packing
f. O-ring seal
g. V-ring seal
h. Piston cup packing
i. Piston ring seal

RESERVOIRS AND TANKS

Reservoirs and tanks are containers for holding the working fluid in fluid power systems. In hydraulic systems, the container, usually called a reservoir, holds hydraulic fluid at atmospheric pressure. The fluid is drawn into the pump inlet from the reservoir and returns through return lines and drains. In pneumatic systems, the container is usually called a tank. The tank receives compressed air from the compressor and holds it at the working pressure until it is needed. Used air is not returned to the tank.

HYDRAULIC RESERVOIRS

A hydraulic reservoir is far more than a container for the hydraulic fluid. Proper design and construction of the reservoir is of key importance to the operation of a hydraulic power system. Characteristics of the reservoir include the following:

- Allows dirt and foreign particles to settle to the bottom and, thus, be removed from the working fluid
- Large surface area to remove heat from the oil
- Large volume to contain all oil that might drain into it from the system
- Adequate air space to allow for thermal expansion of the oil
- Maintains high oil level to prevent air from being drawn into the pump inlet
- Allows entrained air to leave the oil without being drawn into the pump inlet
- Allows for ease of maintenance and cleanup

Figure 1 illustrates a hydraulic reservoir that is suitable for most industrial applications. It is constructed of welded steel plates and coated inside with a protective coating to prevent rust and corrosion due to water or impurities in the oil. The legs or risers supporting the reservoir should have a height of at least six inches to allow adequate airflow across the bottom of the reservoir for oil cooling. The top of the reservoir is a steel plate that bolts into place and usually supports the pump and pump drive.

The reservoir should be as large as space permits to allow better cooling of the oil and to contain a large enough volume of oil that there is time for particles to settle out of returned oil before it is returned to the pump. The

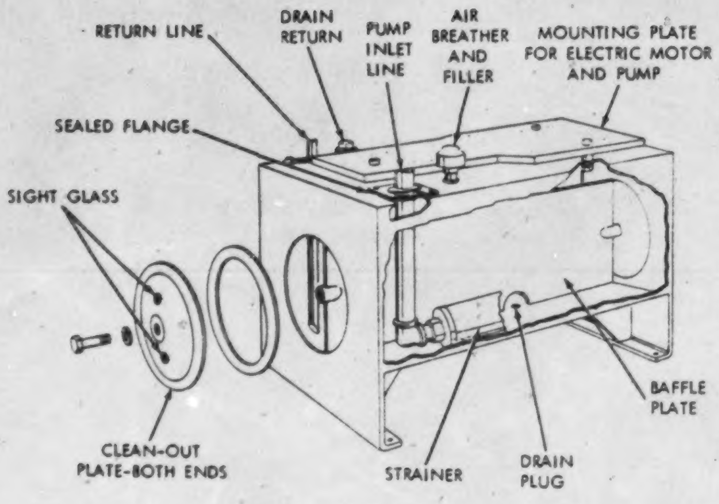


Figure 1. Reservoir Construction.

minimum allowable size of the reservoir is determined by the largest of two factors. The reservoir must be large enough to contain all oil that may drain into it from the system. In systems with large cylinders or long piping runs, this is often the deciding factor. In other systems, the reservoir size is based on pump capacity. Reservoir capacity should be at least three times the gallon per minute rating of the pump.

Reservoirs are generally rectangular in shape with the depth approximately equal to the width. If the reservoir is too shallow, the wall area may not be sufficient for proper cooling of the oil; if it is too deep and narrow, there may not be sufficient surface area for the removal of air bubbles in the oil.

The reservoir contains an internal baffle that is about 70% of the height of the maximum oil level. Oil is returned to the reservoir on one side of the baffle and withdrawn on the other side. This causes the returned oil to remain in the reservoir for the maximum time for removal of air bubbles, particles, and heat energy. The return line extends to within two pipe diameters of the bottom of the tank to prevent foaming of the returning oil. The pump inlet line and strainer are located near the bottom of the tank to prevent a "whirlpool" effect, which would carry air into the pump.

The lower surface of the reservoir is dished or sloped to a drain plug located at the lowest point for removal of all sludge and water during draining. The filler cap on the top of the reservoir is equipped with an air breather that allows air to enter or leave the tank as the oil level changes. A filler is incorporated to prevent contamination from entering with the air. Each end of the reservoir contains a large clean-out plate that may be removed for complete cleaning of the reservoir interior when the system oil is changed. This plate may also contain sight glasses that are used to determine the oil level in the reservoir. Vertical glass tubes can also be used as sight glasses.

The location of the reservoir should allow free airflow around all sides for efficient oil cooling and easy cleanup of any spilled or leaking oil. The location should also afford easy access to the sight glass and ease of maintenance. The reservoir should be cleaned thoroughly at every oil change, as most oil contaiminants accumulate in the bottom of the reservoir.

PNEUMATIC TANKS

The air tank of pneumatic power systems is a container for storing compressed air. Like the reservoir of the hydraulic system, the air tank is an essential component for proper fluid conditioning. Much of the dust contained in the air entering the compressor is removed by the intake filter, but a significant amount is passed on into the system. When the air is compressed and cooled, the moisture it contains condenses and must be removed. Both of these fluid contaminants are removed in the air tank. A drain plug at the bottom of the tank may be removed to allow condensed water to drain out and carry with it dust, dirt, and any rust or corrosion particles that may be present. In many systems, this drain is automatic and cycles whenever a preset amount of liquid water has accumulated.

The size of the air tank varies from one system to another, depending on the use of the pneumatic power system. The tank should be large enough to allow for the condensation of most of the moisture while air is in the tank and should be located so there is adequate ventilation for cooling the air.

TEMPERATURE CONTROL

Both hydraulic and pneumatic power systems require that the temperature of the working fluid be within the proper range. When hydraulic systems are used in extremely cold conditions, it is sometimes necessary to heat the oil to maintain the proper viscosity. Under most operating conditions, the function of temperature control devices is to remove excess heat from the system.

COOLING IN HYDRAULIC SYSTEMS

Heat is generated in hydraulic systems by several components. Most oil heating occurs in the pump, pressure relief valves, and directional control valves, although small amounts are also produced in pistons, motors, and piping. This heat energy raises the temperature of the oil and must be removed to maintain the oil at the proper operating temperature. Module FL-02, "Fluid Properties and Characteristics," describes the problems arising from overheating the hydraulic fluid.

In many hydraulic systems, waste heat is removed primarily through the walls of the reservoir. Air circulating over the outer surfaces of the reservoir cools the walls and the fluid inside. Some reservoirs are equipped with cooling fins. A fan can be directed at the reservoir in order to reduce the temperature enough to overcome minor heating problems.

Larger systems often employ heat exchangers to remove excess heat and maintain oil temperature. Water-cooled heat exchangers consist of a bundle of tubes, which carry the hydraulic fluid, surrounded by a shell, which carries cooling water. Heat is conducted from the oil, through the walls, and into the water. The tubes carrying the oil contain turbulators, which results in turbulent oil flow to bring all the oil in contact with the walls. The heat exchanger is usually located in the return oil line so that oil returns to the reservoir through the heat exchanger. The flow of cooling water can be controlled by temperature sensors in the reservoir.

Air-cooled heat exchangers consist of a series of finned tubes, which carry the oil to be cooled, and a fan for forcing air over the tubes. This type of heat exchanger is usually less expensive to purchase and operate, but is less efficient than the water-cooled type.

COOLING IN PNEUMATIC SYSTEMS

The primary purpose of fluid cooling in pneumatic systems is to remove water vapor from the compressed air. When air is compressed, some of the water vapor it contains condenses as liquid water. Lower air temperatures result in more condensation. Since the compressor also raises the temperature of the air, the water vapor does not condense immediately, and more condensation occurs when the air temperature drops. If moist air enters the distribution piping, it will cool in the pipes and result in liquid water throughout the distribution system. The presence of this liquid water is not usually eliminated entirely, but it must be reduced to alleviate problems.

In many smaller pneumatic systems, air cools in the air tank by conduction of heat energy through the walls of the tank. This removes most of the moisture and the remainder is removed by filters in the distribution system. Larger systems often employ a heat exchanger in the air circuit between the compressor and the tank. This is usually a water-cooled heat exchanger in which the compressed air flows across water-filled tubes with fins, thereby cooling the air before it enters the tank and speeding the condensation process. The liquid water is still collected in the bottom of the air tank.

FILTERS AND STRAINERS

Both hydraulic and pneumatic systems employ filters to remove particles from the working fluid. Proper operation and maintenance of these filters is of prime importance in the operation of the system. All fluid power systems include seals that must prevent leakage around accurately machined moving metal parts. The presence of particles in the working fluid destroys these seals and damages the metal surfaces.

TYPES OF HYDRAULIC FILTERS

Oil filters for hydraulic systems are available in three basic types: size or mechanical filters, absorbent filters, and adsorbent filters.

Mechanical filters are the most widely used and are available in a wide range of sizes and configurations. In this type filter, also called a strainer, oil is forced through a material containing many small openings. Particles too big to pass through the openings are separated from the oil. The most common type of mechanical filter is shown in Figure 2. The filter element consists of finely woven metal screen, fabric, or specially treated paper. The filter element is folded to provide the maximum surface area for filtration. Other types of mechanical filters employ a thick layer of felt or cellulose or a stack of disk-shaped metal elements with small spaces between them. Magnetic rods are often included to attract and hold any iron or steel particles that

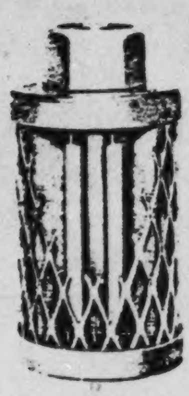


Figure 2. Cutaway View of Take-Apart Sump-Type Filter, Showing the Position of the Magnetic Rods.

may be present. Mechanical filters are usually rated by the diameter of the openings in the filter element in microns. A micron is one-thousandth of a millimeter, or 0.000039 inches. Standard filters are usually in the range of 50 to 150 microns, but some special purpose filters have openings of only 5 microns. These are used to protect sensitive elements such as servo valves. One of the major advantages of the most popular mechanical filters is that they can be cleaned and reused almost indefinitely, whereas other filters are used once and replaced.

Absorbent filters employ porous or permeable materials as filter elements. Materials used include cotton, paper, wood pulp, cloth, and asbestos. Absorbent filter elements do not simply block the passage of particles — as do mechanical filters — but absorb and trap the particles within the filtering material. These filters generally remove particles of smaller size that may be passed by most mechanical filters; however, they do not remove any chemical products of oil oxidation.

Adsorbent filters remove impurities by causing the particles to cling to the surface of the filter element and, in some systems, by chemical action. Materials used in these filters include activated clay and chemically treated paper. Charcoal and Fuller's earth are rarely used because they tend to remove important oil additives.

LOCATION OF HYDRAULIC FILTERS

Filters may be located in several places in hydraulic systems. The most common type is the suction-type filter, also called a sump strainer, which is located inside the reservoir on the end of the pump inlet line. This filter is usually a wire screen mechanical filter. It is the least expensive filter; however, because of several disadvantages, it is considered the minimum acceptable protection and the least effective filter. The major problem with this filter location is its inaccessibility for inspection and maintenance. The reservoir must be drained and opened before the filter can be inspected or cleaned. If the filter becomes clogged, the pump may starve for oil, resulting in pump damage or improper operation.

These problems may be overcome by installing the filter in an external portion of the suction line. Suction filters are often provided with a bypass that opens to allow unfiltered oil to flow to the pump if the filter is clogged. Several types of indicators may be included to indicate the condition of the filter without opening the system — a lever that indicates the loading of the filter element, a plunger that extends when the bypass opens, and an electrical switch that controls an indicator light. In all cases, these indicators are activated by the pressure drop across the filter element.

It is extremely important that a suction filter be sized to accommodate the pump capacity. The only force available to deliver oil to the pump inlet is the force of atmospheric pressure on the surface of the oil in the reservoir. Therefore, only a small pressure drop can be tolerated across the filter element. If the filter is too small, it will restrict the flow to the point of starving the pump.

Figure 3 shows a high-pressure line filter. This type of filter is located in the high-pressure oil line downstream from the pump. It is the most expensive type, as its casing must withstand the full operating pressure of the system. This filter location has several serious disadvantages as compared to suction filters. It does not protect the pump from contaminants entering it from the reservoir. If the filter becomes clogged, the element may collapse because of the oil pressure and the filter becomes inoperative. High-pressure line filters also result in a pressure drop, thus reducing the effective pressure of the system. Advantages of this filter location include ease of service and ease of filtering out extremely small particles. This is because there is more pressure available to force oil through the smaller holes required to remove very small particles.

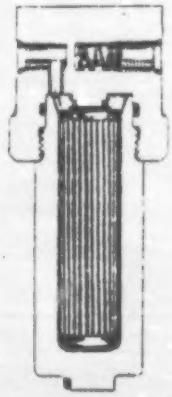


Figure 3. Cutaway View of High-Pressure Line Filter.

Oil line filters may also be located in the return line to the oil reservoir. This arrangement removes the filter from the high pressure part of the system but introduces other problems. Oil line filters become loaded more quickly because contaminants have no opportunity to settle out in the reservoir, and the oil pressure in the return lines is raised. Double-acting cylinders may return oil to the reservoir at a rate much higher than the pump delivery rate. Therefore, return line filters must be sized for the maximum oil return flow rate rather than the pump delivery rate.

The filters discussed thus far have all been full-flow filters. This means that all oil flowing through the system must pass through the filter element. Some systems employ proportional filtering in which only a portion of the oil passes through the filter on each trip through the system. In such a system, also called bypass filtering, the filter may be located in the line that returns oil to the reservoir from the pressure relief valve, in a bypass off the main supply line, or in a bypass off the return line from directional control valves and working components. This filtering scheme allows the system to continue to function with the filter clogged but does not provide the protection of full-flow filtering.

PNEUMATIC FILTERS

Filters are normally located at two points in pneumatic systems. Intake filters remove particles from the intake air and protect the compressor. Air-line filters are located in the air line near the driven components.

Intake filters are usually either dry surface filters or oil-bath filters that use an absorbing material soaked in oil to trap particles. They remove larger particles that might damage the compressor but do not usually remove smaller particles that could damage working components of the system. These particles are removed later by air-line filters.

Even though many contaminants are removed from the air of a pneumatic system by the intake filter and by condensation in the air tank, some contamination is always present in the air lines leading to the working components. These include dust particles, water vapor and liquid, and pipe scale. Air-line filters remove these contaminants just before the air is used. The two major types of air-line filters are the mechanical filter and the absorbent filter.

Figure 4 shows a centrifugal, mechanical air-line filter. It consists of four rotating disks through which the air passes. Airflow through the filter causes the disks to rotate. The rotation causes any heavy particles, such as dust or water droplets, to be thrown out of the air stream by centrifugal force. These particles collect on the sides of the filter housing and are carried to the bottom of the housing by the water that is removed from the air line.

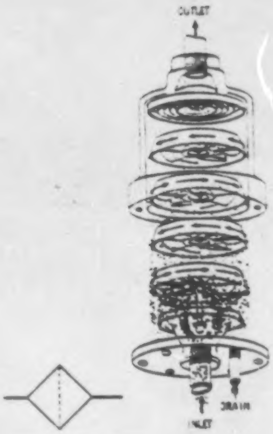

OUTLET
DRAIN
INLET

Figure 4. Mechanical Filter.

Figure 5 shows an absorption-type air filter. In this filter, air enters baffles that swirl the air to remove larger particles by centrifugal force. These particles fall past the quiet zone baffle and are trapped. The main filter element is a cellulose surface-type filter, or an absorption element of some other material, that allows the air passage but traps contaminants. In some filters of this design, the filter element is made of porous brass. Water droplets are removed primarily by centrifugal action and collect in the bottom of the filter. The filter may be drained either manually or automatically.

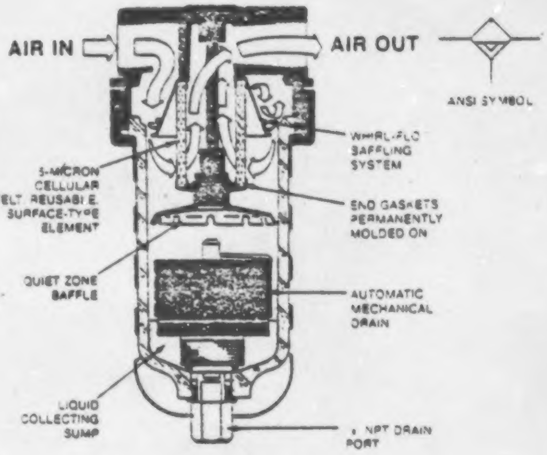

AIR IN
AIR OUT
ANSI SYMBOL
WHIRL-FLO BAFFLING SYSTEM
5-MICRON CELLULAR FELT REUSABLE SURFACE-TYPE ELEMENT
END GASKETS PERMANENTLY MOLDED ON
QUIET ZONE BAFFLE
AUTOMATIC MECHANICAL DRAIN
LIQUID COLLECTING SUMP
NPT DRAIN PORT

Figure 5. Operation of Air Filter.

Air dryers are devices used to remove all the moisture from compressed air to deliver dry air to the point of application. They consist of a cartridge containing a desiccant material that reacts chemically with liquid water or water vapor to remove it from the air stream.

AIR PRESSURE REGULATORS

Air compressors are usually set to turn ON when the pressure in the air tank drops below a preset level and to turn OFF when the pressure rises to another preset level. Thus, the pressure of the delivery system varies during normal operation. Pressure drops in lines and the simultaneous operation of several pieces of equipment may also affect air pressure at any point in the system. Air pressure regulators are used near working components to deliver compressed air to that component at a constant pressure.

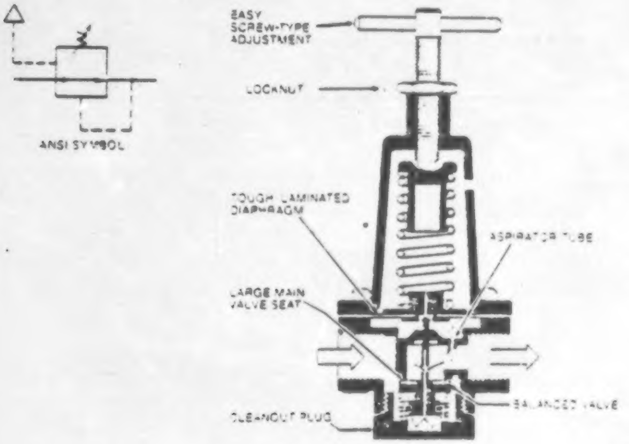


Figure 6. Air Pressure Regulator.

Figure 6 shows a typical air pressure regulator. It consists of a disk-shaped valve operated by a vertical rod. The rod is driven by forces applied by a spring and by air pressure on a diaphragm. The spring forces the rod down to open the valve and is adjustable to set the operating pressure of the regulator. Air pressure from the downstream side of the regulator causes an upward force on the diaphragm and, thus, on the operating rod. If the downstream pressure is at or above the preset level, the valve remains closed and no air flows. If the pressure is below the preset level, the force of the spring exceeds the force on the diaphragm and the valve is forced open until the pressure is restored at the proper level.

AIR-LINE LUBRICATORS

Air will act as neither sealant nor lubricant in pneumatic systems; therefore, oil must be added to the air stream to perform these functions. This is accomplished with the air-line lubricator shown in Figure 7. Air from the supply line enters the bowl of the lubricator to produce a pressure on the surface of the oil equal to the static pressure of the supply line. The air flowing through the lubricator travels through and around a small tube, called a mist generator. Because the air has a greater velocity in the mist generator, its static pressure is less than in the supply line and bowl. The greater pressure in the bowl forces oil to flow up the siphon tube and drip down into the mist generator (Bernoulli' Theorem, see Module FL-01, "Introduction and Fundamentals of Fluid Power"). Oil flow may be adjusted by a small needle valve at the top of the siphon tube. Air flowing through the mist generator breaks the oil droplets into a fine mist, which is carried along with the air stream for lubrication and sealing. Larger oil droplets are carried up to 20 feet in the air stream. Smaller droplets travel as far as 300 feet. For maximum efficiency, the lubricator should be located near the working component. Generally, the volume of air in the air line between the lubricator and the working component should not exceed the volume of the working component.

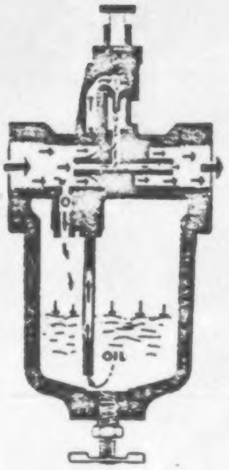


Figure 7. Lubricator with a Sight-Feed Glass.

FRL UNITS

In most pneumatic systems, the air-line filter, pressure regulator, and air-line lubricator are combined in a single unit called a filter-regulator-lubricator (FRL) unit. Figure 8 shows one common FRL unit configuration in common use. Usually, these units are located near the working component. No more than two components should be operated from one FRL unit.

SEALING DEVICES

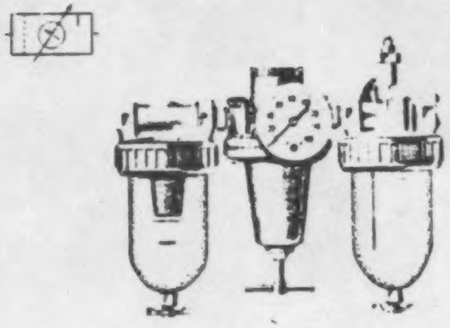


Figure 8. FRL Unit.

Both hydraulic and pneumatic systems require sealing devices to contain internal pressure and prevent leakage of the working fluid. Several types of seals are common in fluid power systems. Static seals are those between components that do not move with respect to one another, such as between the walls and end of a cylinder. Dynamic seals are those that seal components that do move relative to one another, such as between a cylinder and piston. Positive seals are designed to prevent all fluid flow between two components. The seals between a piston and cylinder are positive seals. Nonpositive seals are designed to allow a small amount of oil flow through the seal at all times, such as the seals between the body and spool of a directional control valve. Nonpositive seals are the result of two closely mating rigid surfaces with no flexible sealing element. Positive seals always involve a flexible sealing material that forms a tight fit with the two rigid surfaces.

COMPRESSION PACKINGS

Compression packings are static seals between two rigidly attached components, as shown in Figure 9. The seal material is a fiber gasket positioned between the two components to be sealed. The bolts holding the components together can be tightened, thereby compressing the gasket and producing a positive seal. These seals provide long, trouble-free service and need not be serviced unless the seal is broken by removing one of the components.

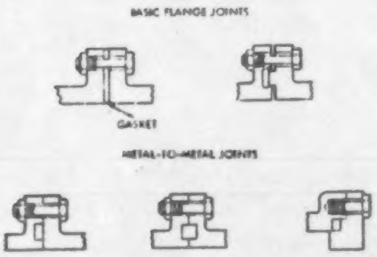


Figure 9. Static Seal Flange Joint Applications.

O-RINGS

O-rings, the most widely used seals for hydraulic systems, are molded synthetic rubber seals with round cross sections. These rings are available in a wide range of sizes. O-rings provide effective dynamic seals through a wide range of pressures and temperatures, seal for movement in both directions, and result in low operating friction for moving parts.

Figure 10 shows the installation of an O-ring in an annular groove in a piston. (Note: Clearances are greatly exaggerated for explanation.) The O-ring is compressed slightly at both diameters, creating a static seal between the two surfaces (Figure 10a). When pressure is applied (Figure 10b), the O-ring is forced against the surface of the groove and the cylinder wall to provide a positive seal in either direction. O-rings are widely used in applications involving sliding motion but are not well suited for rotational motion or applications where vibration is excessive.

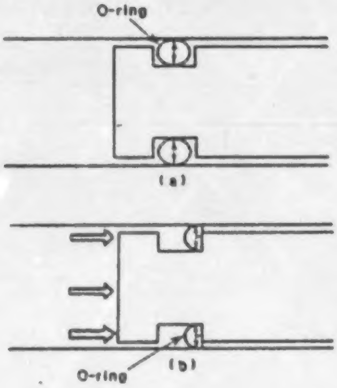


Figure 10. Operation of O-Ring.

At high pressures, the O-ring may extrude into the space between the two mating parts, as shown in Figure 11a. This damages the O-ring and quickly destroys the seal. This can be prevented by installing a back-up ring (Figure 11b). If pressure is to be applied in both directions, a back-up ring must be installed on both sides of the O-ring.

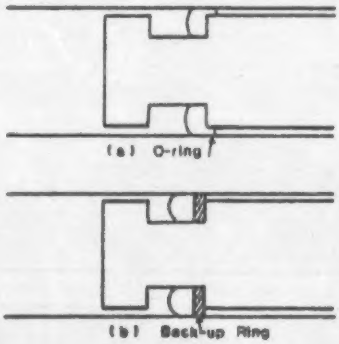


Figure 11. Back-up Ring Prevents Extrusion of O-Ring.

V-RINGS

V-rings are compression fittings used in all types of reciprocating seals. This type of seal is common in rod and piston seals in hydraulic and pneumatic cylinders and in pumps and compressors.

Figure 12 shows a V-ring seal installed as a rod seal. The open end of the V is always installed facing the pressure. In applications where pressure is applied in both directions, two sets of V-rings are required — one facing each direction. V-rings may be used singly or in stacks and are compressed by a flanged follower. Proper tightening of the follower is essential, as too much tension will cause rapid wear of the seal. V-rings are available either as unbroken rings or as split rings. When installed, the split rings will overlap slightly. Compressing the seal will align and seal the joint. V-rings should not be trimmed for an exact fit with no tension applied.

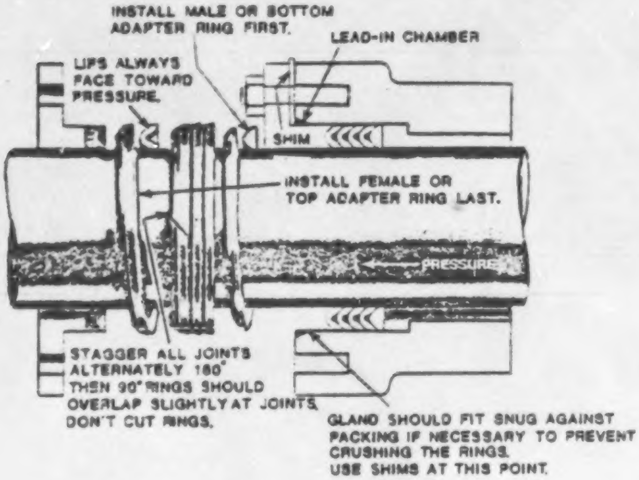

INSTALL MALE OR BOTTOM ADAPTER RING FIRST.
LEAD-IN CHAMBER
LIPS ALWAYS FACE TOWARD PRESSURE.
SHIM
INSTALL FEMALE OR TOP ADAPTER RING LAST.
PRESSURE
STAGGER ALL JOINTS ALTERNATELY 180° THEN 90° RINGS SHOULD OVERLAP SLIGHTLY AT JOINTS. DON'T CUT RINGS.
GLAND SHOULD FIT SNUG AGAINST PACKING IF NECESSARY TO PREVENT CRUSHING THE RINGS. USE SHIMS AT THIS POINT.

Figure 12. Application of V-Ring Packings.

PISTON CUP PACKINGS

Piston cup packings are designed specifically for sealing pistons in hydraulic and pneumatic cylinders and in reciprocating pumps and compressors. They offer the best service life for these applications, require the minimum recess space, and are easily and quickly installed. They are cup shaped with a hole in the center. Figure 13 shows piston cup packings installed in single-acting and double-acting cylinders. Since the applied pressure forces the cup open and into contact with the cylinder wall, piston cup packings can handle extremely high pressures.

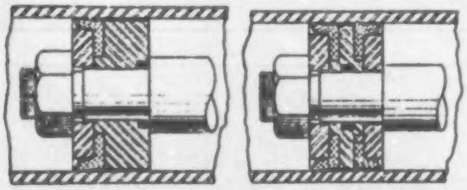

a. Single-acting Cylinder   b. Double-acting Cylinder

Figure 13. Piston Cup Packings.

PISTON RINGS

Piston rings are circular seals with a rectangular cross section used to seal pistons in cylinders or pumps. They may be used singly for low pressures or multiply for higher pressures, as shown in Figure 14.

Metallic piston rings are made of cast iron or steel and are plated with zinc phosphate or manganese phosphate to resist rust and corrosion. These types of piston rings offer considerably less resistance to motion than do rubber seals.

A variety of other materials can also be used for piston rings in fluid power systems. The most common is Teflon. These rings are available in a variety of styles for specific applications.

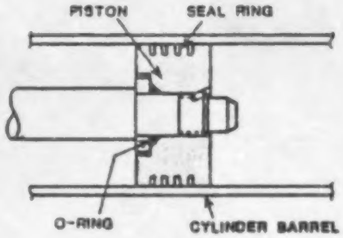


Figure 14. Use of Piston Rings for Cylinder Pistons.

WIPER RINGS

Wiper rings are seals designed to prevent foreign matter from entering a cylinder. They do not seal against pressure. Figure 15 shows the shape and installation arrangement of a wiper ring. They may be made of brass, but synthetic rubber is a more common material.

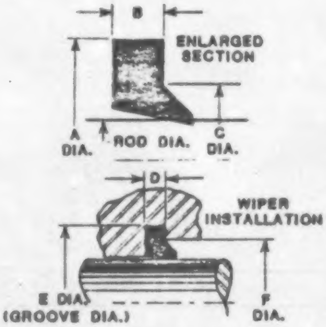


Figure 15. Wiper Rings.

SEAL MATERIALS

Several materials are commonly used as seals in hydraulic and pneumatic systems. Natural rubber is seldom chosen because it swells and deteriorates with time and in the presence of most oils. Metal seals are commonly used as piston rings in pumps and compressors. Other common seal materials are discussed below.

Leather is the oldest material used for cylinder packing and still is used today. Modern leather seals are impregnated with synthetic rubber compounds to eliminate problems arising from its porous nature. Leather seals cannot be used at temperatures above 200°F but provide satisfactory service at temperatures as low as -60°F. Leather does not accumulate abrasive materials and, therefore, will not damage moving metal surfaces. The continued movement of leather against the surface has a polishing effect, which actually improves the surface finish. Leather has good lubricating properties and low operating friction and resists extrusion. It cannot be used with fluids that are either excessively acidic or alkaline.

Buna-N is a synthetic rubber material widely used for seals in systems using oil as a fluid or lubricant. It has an operating temperature range of -50°F to 200°F. A similar material, Buna-S, is used with water and synthetic fluids. These synthetics are more resistant to acidic fluids, as compared to leather; however, they are worn more quickly by rough surfaces and, thus, require a smoother finish for moving parts. They are used for O-rings and V-rings and often include a fabric for extra strength in piston cup packings.

Viton is another synthetic rubber material that is widely used for hydraulic seals. Its major advantage is satisfactory operation in a temperature range of -20°F to 500°F.

Neoprene is a synthetic rubber material sometimes used for O-rings and other seals. Its operating temperature range is -65°F to 250°F.

Silicone rubber has an operating temperature range of -90°F to 450°F but has low tear resistance. Because of its susceptibility to damage, it is not used for reciprocating seals. Silicone rubber is widely used for rotating shaft seals.

Tetrafluoroethylene (TFE), commonly known by the trade name Teflon, is the most widely used plastic material for seals in many applications. Its advantages include extremely low friction and resistance to chemical breakdown at temperatures as high as 700°F. Its major drawback is its tendency to flow under pressure to form very thin films. This is greatly reduced in some seal materials by including graphite or fibers of glass, metal, or asbestos. Teflon is used primarily for piston rings.

A variety of other synthetic rubber and plastic compounds are sometimes used but none are as common as those listed above.

SUMMARY

Fluid conditioning and maintenance are essential to the operation of all fluid power systems. In hydraulic systems, the reservoir is the central element in storage, conditioning, and maintenance of the hydraulic fluid. It removes waste heat from the fluid, allows particles to settle out and air bubbles to escape, and usually contains the filter that removes smaller particles that are carried along with the oil. In pneumatic systems, the air tank serves as a container in which most of the water vapor is condensed and removed. Both types of systems require filtration of the working fluid. Pneumatic systems also require that a small quantity of oil be added to the air stream to lubricate and seal moving parts. Excess heat may be removed from the fluid in either type system by the use of heat exchangers.

One of the major reasons for conditioning the fluid in fluid power systems is to protect the seals of the system. The most critical seals are the positive dynamic seals in moving parts such as pistons, pumps, and fluid motors. A variety of seal materials and configurations can be used, but proper operation and extended life of all seals depends on the condition of the fluids that are in contact with them.

EXERCISES

1. Draw the components of a hydraulic fluid reservoir and describe the construction and purpose of each component and feature.
2. Compare the functioning of the reservoir in a hydraulic system and the air tank in a pneumatic system for both fluid storage and conditioning.
3. Explain methods and importance of removing heat energy from the fluid in pneumatic and hydraulic systems.
4. Explain the functioning of the three major types of hydraulic filters and the reasons for the relative popularity of each.
5. List the possible locations for the filter in a hydraulic system, and describe the advantages and disadvantages of each.
6. Explain the operation of each of the major sections of a pneumatic filter-regulator-lubricator unit and the necessity of each for proper system performance.

7. Explain the construction and operation of the following seals:
   a. Compression packing
   b. O-ring
   c. V-ring
   d. Piston cup packing
   e. Piston rings
   f. Wiper rings
8. List the commonly used seal materials and describe the characteristics and applications of each.

LABORATORY MATERIALS

Hydraulic reservoir
Sump strainer
Suction line filter
High-pressure line filter
FRL unit
Various hydraulic and pneumatic cylinders with a variety of seal types and materials.

LABORATORY PROCEDURES

This laboratory consists of the disassembly, inspection, and reassembly of a variety of fluid power components.

1. Observe the instructor in the disassembly and assembly of the various fluid power components. Make notes of procedures and materials used in each component.
2. Disassemble each component using the methods demonstrated and explained by the instructor. Make notes or working sketches during the process to assure proper reassembly of the component.
3. Sketch the major parts of the component. Use a separate sheet of paper for each.

4. Examine the component for wear or damage. Record the condition of each component on the sheet with the drawing.
5. Reassemble each component.
6. Write a brief report describing each component. Include the materials used in its construction, the purpose of the component, its operating characteristics, and any wear or damage. Also, include any problems or difficulties encountered in assembly or disassembly of the component.

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Stewart, Harry L. Pneumatics and Hydraulics. Indianapolis, IN: Theodore Audel and Co., 1976.

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GLOSSARY

Absorbent filtration: The removal of particles from hydraulic oil by passing the oil through an absorbent material that traps the particles within the material.

Adsorbent filtration: The removal of particles and chemical compounds from hydraulic oil by passing the oil through a material that attracts particles to its surface and adsorbs some chemicals.

Air tank: A container holding compressed air at the working pressure in a pneumatic system.

Full-flow filtering: Hydraulic filtering system in which all oil is filtered on each pass through the system.

Hydraulic reservoir: A container holding hydraulic oil at atmospheric pressure in a hydraulic power system.

Mechanical filtration: The removal of particles from hydraulic oil by passing the oil through a filter with holes that will not allow the particles to pass.

Proportional filtering: Hydraulic filtering system in which only a portion of the oil is filtered on each pass through the system.

TEST

1. Hydraulic reservoirs and pneumatic air tanks have which of the following functions in common?
   - a. Removal of contaminants from the working fluid
   - b. Removal of heat from the working fluid
   - c. Storage of the working fluid under pressure for future application
   - d. Both a and b
   - e. All of the above
2. Which of the following are characteristics of mechanical hydraulic filters?
   - a. Least expensive type
   - b. Least effective type
   - c. Most common type
   - d. Both a and b
   - e. Both b and c
   - f. All of the above
3. Which of the following are characteristics of mechanical pneumatic filters?
   - a. Contain absorbent elements to remove small particles
   - b. Used primarily for intake filters
   - c. Ineffective in removing water droplets
   - d. Both a and b
   - e. None of the above
4. Which seal materials have the highest operating temperatures?
   - a. Buna-N and leather
   - b. Buna-S and silicone rubber
   - c. Viton and neoprene
   - d. Teflon and viton
   - e. Tetrafluoroethylene and Buna-N
5. Which of the following seal types will seal against pressure in either direction of a single seal?
   - a. O-ring
   - b. V-ring
   - c. Piston cup packing
   - d. Wiper ring
   - e. Both a and b
   - f. All of the above

6. Which of the following statements is not true of full-flow filtering?
   a. It is the most common type of filtering in hydraulic systems.
   b. It may be accomplished by either sump strainers or line filters.
   c. It filters all the oil each time it passes through the system.
   d. It is usually accomplished with a mechanical filter.
   e. None of the above. (All are true.)

7. A seal between a piston rod and the end of the cylinder is classified as what type of seal?
   a. Positive, static
   b. Nonpositive, static
   c. Positive, dynamic
   d. Nonpositive, dynamic
   e. None of the above

8. Which type of seal offers the longest life for high-pressure hydraulic cylinders?
   a. O-ring
   b. Piston cup packing
   c. Piston ring
   d. Both a and b
   e. Both b and c

9. Which of the following is not a true statement concerning the sizing of a hydraulic reservoir?
   a. It should have a capacity of at least three times the gallon per minute capacity of the pump.
   b. It should have a capacity greater than the total volume of oil that can drain into it from the system.
   c. It should be as small as practicable to accomplish its function to save space.
   d. It should have a large enough surface area to allow removal of all excessive heat from the oil.
   e. None of the above. (All are true statements.)

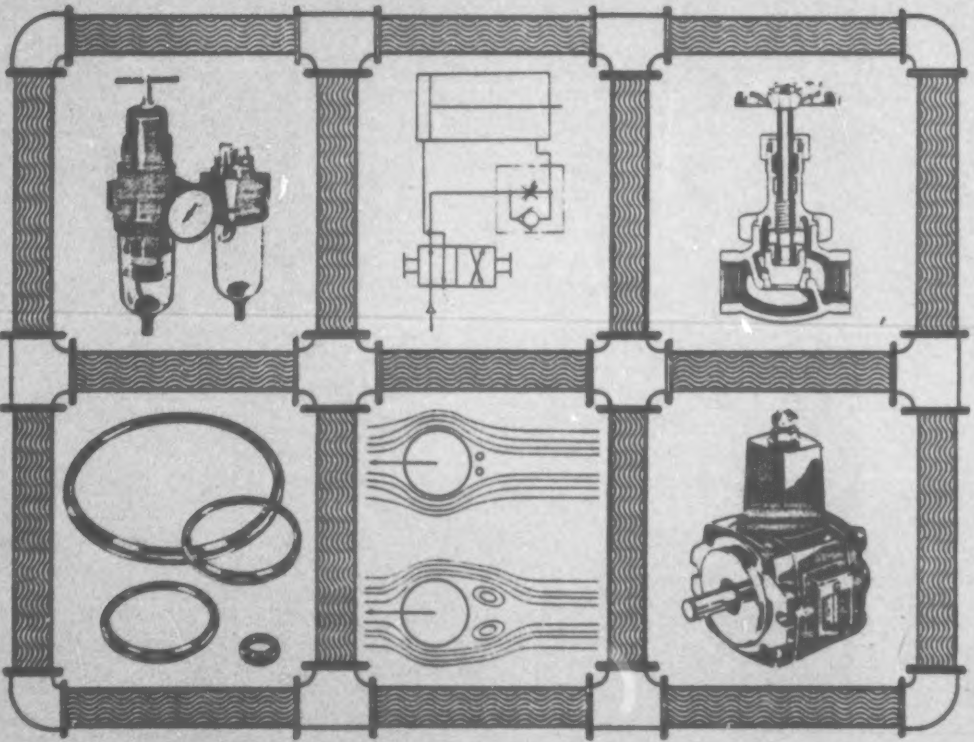
10. Which of the following is not a disadvantage of high-pressure line filters, as compared to other types of hydraulic filters?

   a. Reduced protection for the pump
   b. Greater expense for the high-pressure casing
   c. Reduced filtering ability because smaller holes would produce too much pressure loss
   d. Greater likelihood of the filter element collapsing than with any other type
   e. None of the above. (All are disadvantages of high-pressure line filters.)

ENERGY TECHNOLOGY

CONSERVATION AND USE

FLUID POWER



MODULE FL-04

PUMPS AND COMPRESSORS

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

Pumps and compressors provide the fluid power in hydraulic and pneumatic power systems. Hydraulic pumps are positive-displacement pumps that provide constant liquid flow rates. Air compressors are used in pneumatic systems to compress air from the inlet pressure to the desired pressure level.

This module discusses the construction, types, characteristics, and maintenance of pumps and compressors. In the laboratory, the student will measure the volumetric efficiency of a hydraulic pump and determine the compressed air delivery rate of a compressor.

PREREQUISITES

The student should have completed Module FL-03, "Fluid Storage, Conditioning, and Maintenance."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Draw diagrams of simple positive-displacement and nonpositive-displacement pumps and explain the operation of each.
2. Compare the operating characteristics of positive-displacement and nonpositive-displacement liquid pumps and explain how these characteristics affect pump applications.
3. Explain the following terms:
   a. Slippage
   b. Volumetric efficiency
   c. Overall pump efficiency
4. Sketch the components of the following hydraulic pumps. List the operating characteristics and relative lifetimes of each.
   a. External gear
   b. Internal gear
   c. Gerotor
   d. Lobe
   e. Screw

   - f. Unbalanced vane
   - g. Balanced vane
   - h. Bent-axis piston
   - i. In-line axial piston
   - j. Radial piston

5. Explain the characteristics that determine the applications of the following pump types:
   - a. Gear pumps
   - b. Vane pumps
   - c. Piston pumps
6. Explain the operation of a pressure booster.
7. Calculate the delivery rate of a compressor at its delivery pressure, given the following:
   - a. Free air delivery rate
   - b. Delivery pressure
   - c. Temperature of intake air
   - d. Temperature of output air
8. Explain the importance of cooling in a multi-stage piston compressor and how cooling is accomplished with both air and water.
9. Explain, with diagrams, two methods of unloading the output of reciprocating compressors.
10. Explain the operation of positive-displacement and nonpositive-displacement rotary air compressors.
11. Explain the two most common types of damage to hydraulic pumps and the most important factor in both pump and compressor maintenance.
12. In the laboratory, measure the volumetric efficiency of a hydraulic pump, the overall efficiency of a hydraulic power system, and the delivery rate of an air compressor.

SUBJECT MATTER

THEORY OF PUMPS

The heart of every fluid power system is a device that converts mechanical energy to the energy of a fluid flowing under pressure. In hydraulic systems, this device is called a pump; in pneumatic systems, it is called a compressor. Both pumps and compressors operate according to the same principles. The differences arise from the fact that one uses an incompressible liquid and the other uses a compressible gas. All pumps and compressors can be divided into two classes: positive-displacement and nonpositive-displacement.

POSITIVE-DISPLACEMENT PUMPS

Positive-displacement pumps eject the same volume of fluid into the system for each revolution of the pump drive shaft, regardless of system pressure. The simple piston pump in Figure 1 illustrates the principle of positive-displacement pumps. It consists of a piston that moves back and forth in a cylinder and two check valves (an inlet valve and a discharge valve). As the piston moves to the left, the discharge valve is closed because of the high pressure in the discharge line. This prevents fluid from flowing back into the cylinder from the discharge line. The vacuum created by the piston motion produces a low pressure in the cylinder. Atmospheric pressure on the surface of the oil in the reservoir forces the oil up the inlet line, opening the inlet valve and filling the cylinder.

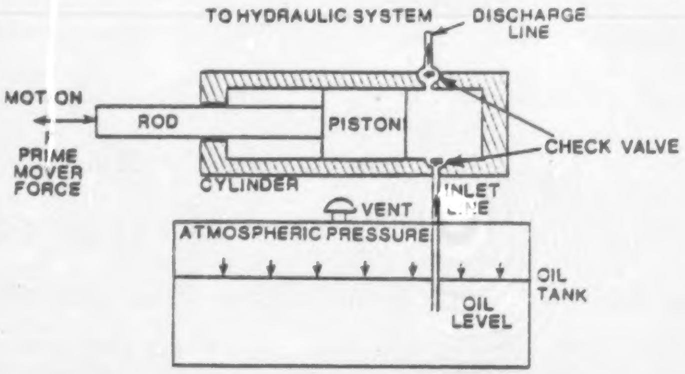


Figure 1. Pumping Action of a Simple Piston Pump.

When the piston moves to the right, the increased pressure on the cylinder closes the inlet valve and opens the discharge valve. The fluid in the cylinder is then forced out through the outlet valve. Thus, for each stroke of the piston, the same constant volume of fluid is delivered by the pump.

Pump slippage is the leakage of oil (or other incompressible liquid) from the output side of the pump around pump components to the inlet side. Slippage is very small in positive-displacement pumps because of the very small clearances between moving parts. Thus, large increases in delivery pressure cause very small decreases in delivery rate. Positive-displacement pumps have a delivery rate that is almost constant at any pressure. The delivery pressure is determined by the resistance to fluid flow in the high-pressure fluid circuit. If the pump outlet is open to the atmosphere, the delivery pressure is atmospheric pressure. If the high-pressure circuit of a hydraulic system is closed, liquid flow is not possible and the pump continues to deliver liquid at the same rate. The pressure increases rapidly until the pump breaks. Therefore, pressure relief valves, which open at a preset pressure, are required to protect the pump. The maximum pressure produced in a hydraulic system is determined by the pressure relief valve — not the pump.

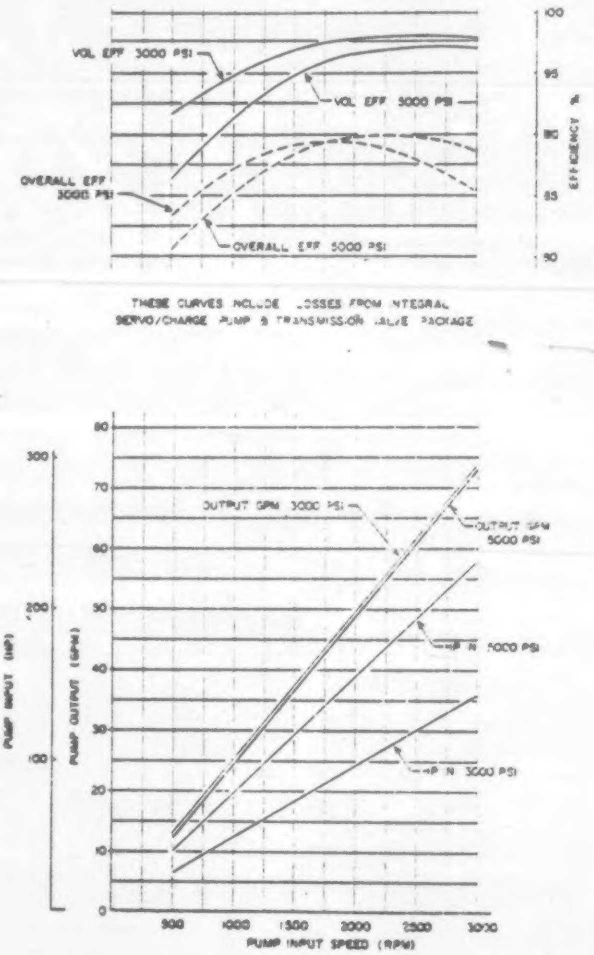
Slippage of positive-displacement liquid pumps is low enough that air can be pumped out of the suction line while liquid is drawn up the line. These pumps are called self-priming because they can begin operation without being filled with liquid.

Most air compressors for pneumatic systems are of the positive-displacement type. Because the working fluid is compressible, there is no danger of a rapid pressure increase. However, if a positive-displacement compressor continues to pump air into a closed container, the pressure will eventually increase to the point of causing damage. In pneumatic systems, the system pressure is limited by a pressure switch, which turns the compressor off at the desired maximum system pressure.

CHARACTERISTICS OF POSITIVE-DISPLACEMENT LIQUID PUMPS

The volumetric efficiency of a pump indicates the percent slippage in the pump. It is the ratio of the delivery rate at operating pressure to the delivery rate if no slippage occurred. Thus, if 10% of the oil leaks back through the pump, the volumetric efficiency is 90%. The volumetric efficiency of a pump increases at higher delivery pressures and decreases at higher pump speeds. This is shown for a particular pump in the example performance curves shown in Figure 2.

The overall efficiency of a pump is the percentage of the mechanical input power that is converted to fluid output power. Some power is always lost because of friction and fluid turbulence. This leads to heating of the pump and liquid. Figure 2 also shows how pump efficiency varies with pump speed at two delivery pressures.



THESE CURVES INCLUDE LOSSES FROM INTEGRAL SERVO/CHARGE PUMP & TRANSMISSION VALVE PACKAGE

Figure 2. Performance Curves for 6-in^3 Variable-Displacement Piston Pump.

The output flow rate of a positive-displacement pump increases proportionately with pump speed. At a fixed delivery pressure, the mechanical input power must also increase proportionately in order to power the pump. Delivery rate is influenced very little by change in pressure, as is shown by the lower graph in Figure 2.

Noise is another important consideration in pump operation. The output of many positive-displacement pumps pulsates and produces noise in the system. In pumps that are small and compact, the noise is transmitted through the liquid to other components. Quiet operation is desirable, and increased noise in a hydraulic system usually indicates pump wear or damage.

NONPOSITIVE-DISPLACEMENT PUMPS

Nonpositive-displacement pumps are pumps in which the fluid delivery rate varies with the delivery pressure. Such pumps produce a maximum pressure with no flow and cannot be damaged by their own pressure.

Figure 3 shows a simple nonpositive-displacement pump. The rotating impeller causes the liquid to rotate and be forced outward by centrifugal force. More liquid is drawn into the pump through the center of the impeller. These pumps have large component clearances and high slippage. If the output port is blocked, the slippage limits the pressure and protects the pump. The maximum pressure possible with nonpositive-displacement liquid pumps is about 300 psi. The large slippage prevents these pumps from removing air from the suction line and drawing liquid to the pump. Thus, they are not self-priming and must be filled with liquid before they can begin operation. Large slippage of nonpositive-displacement pumps also results in quiet operation and long pump life.

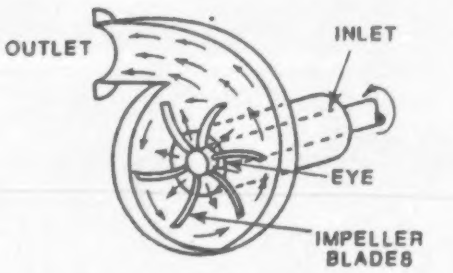


Figure 3. Centrifugal Pump Components.

Nonpositive-displacement pumps are not used in hydraulic power systems because of their low pressures and variable delivery rate. These properties make them desirable for fluid transport applications such as water utility systems and recirculating water systems. Until recently, most air compressors were of the positive-displacement type, but nonpositive-displacement centrifugal compressors are becoming popular. They are also used in most large air conditioners.

HYDRAULIC PUMPS

All hydraulic pumps are positive-displacement pumps. Many types are used, but all fall into three major categories: gear pumps, vane pumps, and piston pumps.

GEAR PUMPS

The external gear pump (Figure 4) consists of two gears enclosed in a close-fitting casing. One of the gears is driven by a motor and, in turn, drives the other gear. A vacuum is created as the teeth unmesh, and oil enters from the reservoir (1). The oil is trapped in the spaces between the gear teeth and casing (2) and carried to the outlet. As the gear teeth mesh on the outlet side, oil is forced out of the pressure port (3). The outlet pressure against the teeth causes heavy side-loading on the shafts (4).

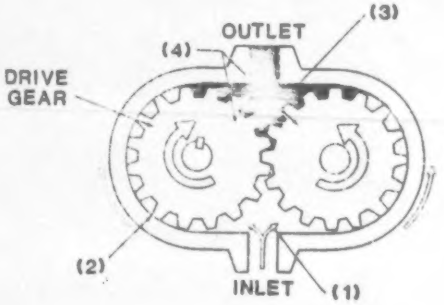


Figure 4. External Gear Pump Operation.

Figure 5 shows an internal gear pump. The inner gear is driven by a motor and drives the outer ring gear. The inner gear has fewer teeth than the outer gear. A crescent seal separates the two gears where the teeth do not mesh. Oil entering the pump (1) is trapped between the gear teeth and the crescent seal (2) and carried to the output. The teeth of the two gears mesh on the output side of the pump (3), forcing the oil through the port (4).

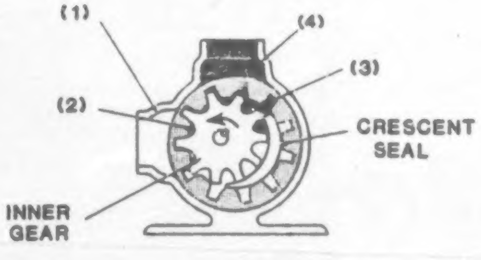


Figure 5. Internal Gear Pump Operation.

Figure 6 is a Gerotor pump. The Gerotor element, the powered element, has one fewer teeth than the outer gear rotor. The gear teeth are shaped so there is always

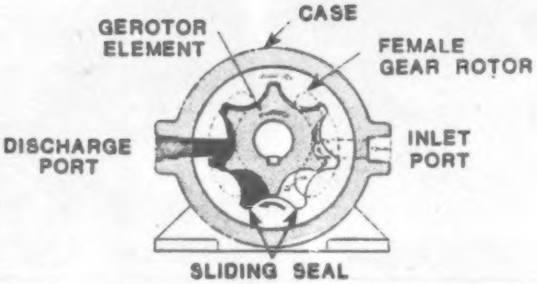


Figure 6. Operation of Gerotor Pump.

a seal at the top and bottom of the pump. The bottom tooth of the Gerotor element forms a seal with the outer gear rotor as it slides across the lower arc of the rotor. This forces oil through the output and draws more oil into the liquid.

Gear pumps are widely used in hydraulic power applications because they are the simplest and least expensive type. Disadvantages include a higher noise level, shorter lifetime, and lower volumetric and overall efficiencies than other pumps. The lower lifetime is the result of wear on gear teeth because of sliding contact and on bearings because of side thrusts. Slippage between gear teeth and the seals and across the faces of the gears results in lowered efficiencies. Gear pumps are suitable for hydraulic power systems that operate at less than full power most of the time and for systems that are used only intermittently. Most mobile hydraulic systems use gear pumps.

Figure 7 shows a variation of the gear pump, called a lobe pump. Both lobes are driven so that the surfaces do not actually come in contact. The characteristics of the lobe pump are similar to those of the internal gear pump, but the noise level is higher. Lobe pumps produce greater output for their size than other gear pumps.

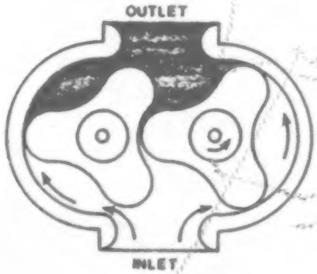


Figure 7. Operation of the Lobe Pump.

Figure 8 shows a screw pump, which is also a variation of the gear pump principle. The three helical screws are sealed in a close-fitting casing. The power rotor is driven by a motor and drives the two idler rotors. Oil is trapped in the spaces between the idler teeth and the side walls of the casing and carried from one end of the pump to the other. The rotors make rolling contact rather than sliding contact (as in gear pumps), and there are no side thrusts on the power shaft. Thus, screw pumps have a long, reliable life. They are also among the quietest and most efficient pumps. Screw pumps are considerably more expensive than any other pump in the gear pump family.

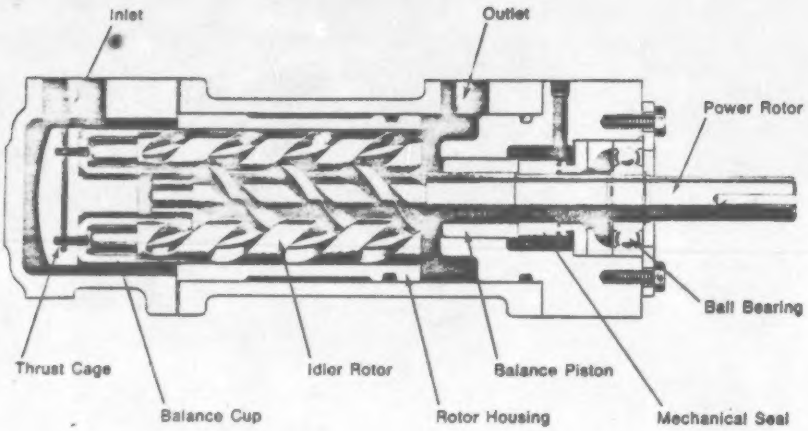

Inlet
Outlet
Power Rotor
Ball Bearing
Thrust Cage
Idler Rotor
Balance Piston
Balance Cup
Rotor Housing
Mechanical Seal

Figure 8. Nomenclature of a Screw Pump.

VANE PUMPS

Figure 9 shows the simplest type of vane pump. It is called an unbalanced vane pump because the rotor is offset from the center of the pump cavity and is subject to side thrusts. The cylindrical rotor has a series of vanes set in slots, which extend to contact the circular cam ring. The vanes may be extended by centrifugal force when the pump is in operation, or by springs. The most common method is to employ channels that direct high-pressure oil from the output to the spaces behind the vanes. As the vanes extend at the top of the pump cavity, oil is drawn into the enlarged spaces between them through grooves in the sides of the pump body (1). After rotating past the top of the cavity, the vanes are forced back into the rotor and the oil is forced through the outlet (2). A side load is exerted on bearings because of pressure imbalance (3).

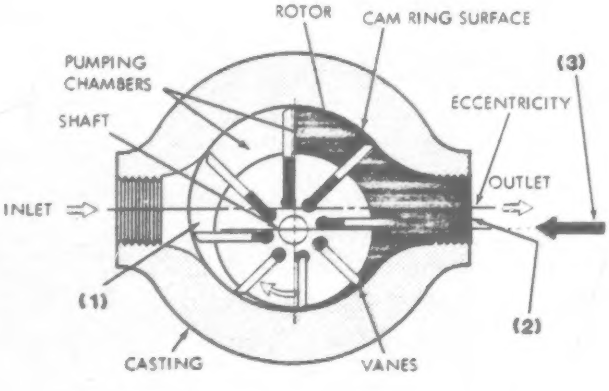

ROTOR
CAM RING SURFACE
PUMPING CHAMBERS
(3)
ECCENTRICITY
SHAFT
OUTLET
INLET
(1)
(2)
CASTING
VANES

Figure 9. Vane Pump Operation.

A balanced vane pump has an elliptical cavity and a centered circular rotor (Figure 10). It has two outlets, two inlets, and pumps on both sides of the rotor. This reduces side thrust on the rotor shaft and gives quieter operation. Because of the lack of side thrust, balanced vane pumps can operate at higher pressures than unbalanced pumps.

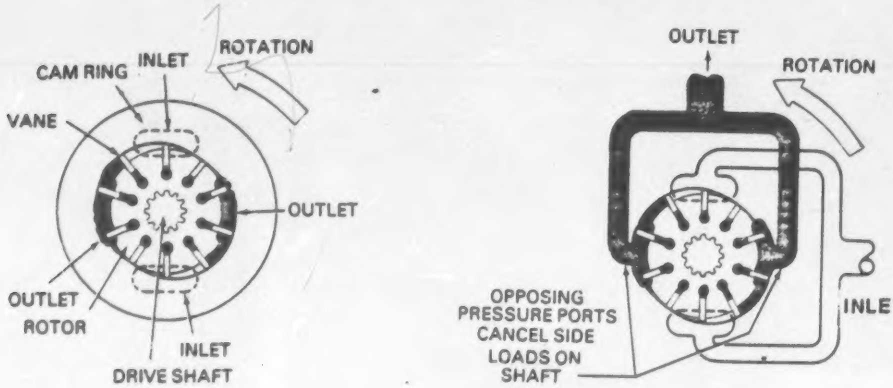

CAM RING
INLET
ROTATION
VANE
OUTLET
OUTLET
ROTOR
INLET
DRIVE SHAFT
OUTLET
ROTATION
OPPOSING PRESSURE PORTS CANCEL SIDE LOADS ON SHAFT
INLET

Figure 10. Balanced Vane Pump Principle.

The pumping rate of an unbalanced vane pump can be varied by moving the center of the cavity with respect to the center of the rotor. The more nearly the rotor is centered in the cavity, the lower the pumping rate becomes. Variable-volume vane pumps have a pressure ring that can be moved within the pump casing. This can be accomplished with a manual adjustment or with an automatic pressure compensator, as shown in Figure 11. The compensator consists of a large spring, which applies a force to keep the pressure ring off center. When the delivery pressure increases, the force applied to the spring by the pressure ring increases, thereby compressing the spring

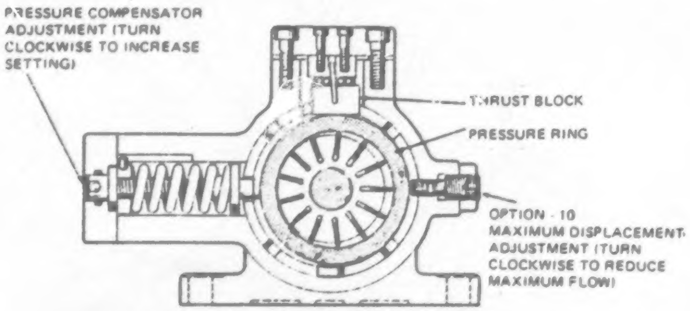

PRESSURE COMPENSATOR ADJUSTMENT (TURN CLOCKWISE TO INCREASE SETTING)
THRUST BLOCK
PRESSURE RING
OPTION - 10 MAXIMUM DISPLACEMENT ADJUSTMENT (TURN CLOCKWISE TO REDUCE MAXIMUM FLOW)

Figure 11. Variable-Displacement Pressure-Compensated Vane Pump.

and reducing the flow rate. If the output port is completely blocked, the pressure ring becomes centered and no fluid flow is produced. This is the only type of positive-displacement pump that has automatic over-pressure protection without using a pressure relief valve. (Other pump types are sometimes protected by pressure relief valves built into the pump casing.)

Vane pumps are generally better in all respects than gear pumps, but they are also more expensive. They are widely used where extended life at fairly constant power loads is required and where the pulsating properties of gear pumps is objectional.

PISTON PUMPS

Two types of piston pumps are in common use, employing two different methods of applying drive power to pistons. Figure 12 shows an axial piston pump. This is called a bent-axis type because of the angle in the rotational axis of the pump. The only stationary part of this pump is the block containing the inlet and outlet ports. As the cylinder block rotates, openings in the cylinders move past the inlet and outlet ports. The pistons reciprocate because of the bend in the pump shaft. At the bottom of the pump, the

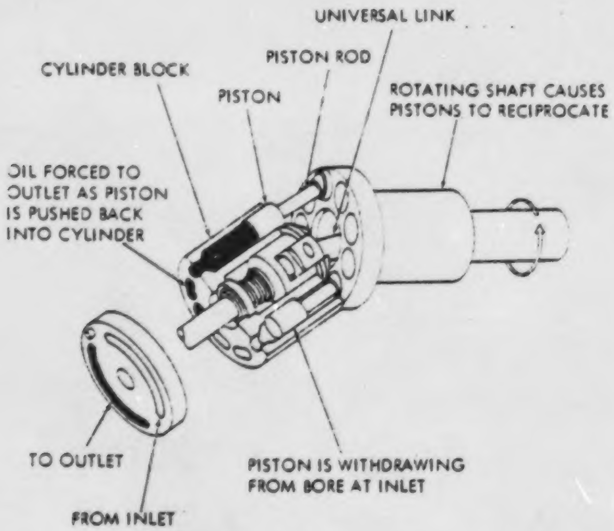

UNIVERSAL LINK
CYLINDER BLOCK
PISTON ROD
PISTON
ROTATING SHAFT CAUSES PISTONS TO RECIPROCATE
OIL FORCED TO OUTLET AS PISTON IS PUSHED BACK INTO CYLINDER
TO OUTLET
FROM INLET
PISTON IS WITHDRAWING FROM BORE AT INLET

Figure 12. Axial Piston Pump (Bent-Axis Type).

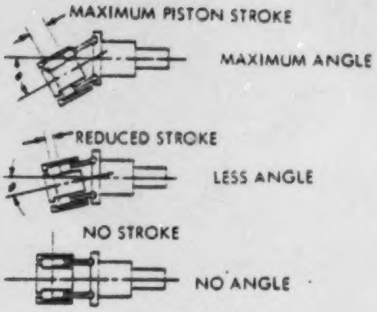

MAXIMUM PISTON STROKE
MAXIMUM ANGLE
REDUCED STROKE
LESS ANGLE
NO STROKE
NO ANGLE

Figure 13. Volumetric Displacement Changes with Offset Angle.

pistons are extended into the cylinders; at the top, they are withdrawn. Thus, oil fills each cylinder from the inlet port and is forced out into the outlet port. The pumping rate depends on the angle between the drive shaft and the cylinder block shaft. The pumping rate of a bent-axis piston pump can be varied by changing the angle, as illustrated in Figure 13.

Figure 14 shows the in-line axial piston pump. It has a straight axis and moves the pistons by means of a rotating shoe plate at a fixed angle to the pump shaft. Pistons withdraw from the bore at the inlet (1) and are forced back in at the outlet (2). The shoe plate rides against a stationary plate, called a swash plate. The angle of the swash plate can be varied to change the pump rate. In many such pumps, the swash plate will tilt in either direction to provide pumping of fluid in either direction in the fluid circuit.

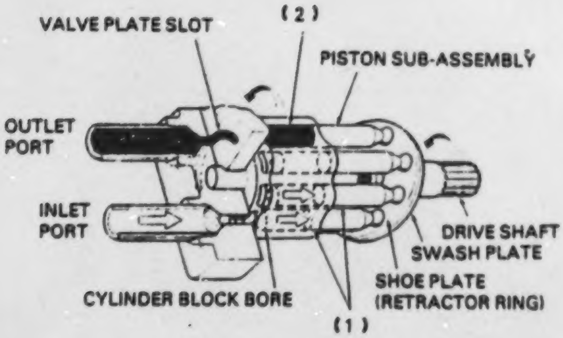

VALVE PLATE SLOT
(2)
PISTON SUB-ASSEMBLY
OUTLET PORT
INLET PORT
DRIVE SHAFT
SWASH PLATE
SHOE PLATE (RETRACTOR RING)
CYLINDER BLOCK BORE
(1)

Figure 14. In-Line Axial Piston Pump.

The radial piston pump illustrated in Figure 15 has a circular case and rotor similar to a vane pump. In this case, however, the rotor carries pistons that ride against the casing. The rotor is off center in the casing so that each piston reciprocates during each revolution of the rotor. The center of the rotor is a stationary cylinder, called a pintle, which contains channels by which oil enters and exits the cylinders and seals the input and output ports against the moving rotor. The pistons are moved outward during the intake stroke by centrifugal force. The output of some radial pumps can be changed by moving the circular casing with respect to the rotor, as in a variable vane pump. Because of their similar construction, vane pumps and radial piston pumps cannot be operated at speeds as high as other pump types. Radial piston pumps are more susceptible to wear than axial piston pumps.

Piston pumps are the most expensive and complicated types, but they are the best in terms of efficiency, quiet operation, and service life. These characteristics are the result of the close seals between the pistons and cylinders. Axial piston pumps can be operated at speeds up to 5000 rpm, providing the greatest power-to-weight ratio and the smoothest flow of any pump type. They can tolerate the greatest fluid viscosity range of any pump. They are also the most difficult to repair in the field.

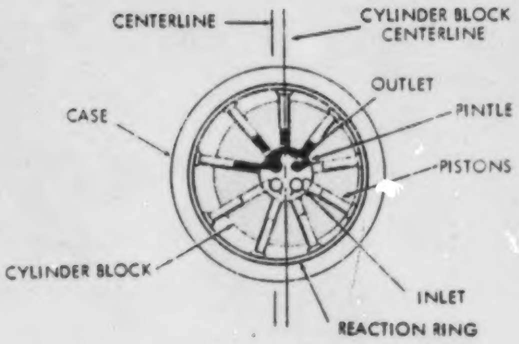


Figure 15. Operation of Radial Piston Pump.

SELECTION OF HYDRAULIC PUMPS

Hydraulic pumps are selected according to the characteristics of the hydraulic system of which they are a part, maintenance requirements, and the cost of the pump. The pressure and flow rates required are determined by the hydraulic actuators used in the system. The pump is chosen to give satisfactory service at the required pressure and flow rate. The type of pump chosen is determined by the following characteristics:

- Delivery pressure
- Service life
- Maintenance requirements
- Dependability
- Efficiency
- Noise level
- Cost

Table 1 lists some of the typical specifications for the most common types of fluid pumps.

TABLE 1. COMPARISON OF VARIOUS PERFORMANCE FACTORS FOR PUMPS.

Pump Type	Pressure Rating (psi)	Speed Rating (rpm)	Overall Efficiency (%)	hp/lb Ratio	Flow Capacity (gpm)	Cost ($/hp)
External Gear	2000-3000	1200-2500	80-90	2	1-150	4-8
Internal Gear	500-2000	1200-2500	70-85	2	1-200	4-8
Vane	1000-2000	1200-1800	80-95	2	1-80	6-30
Axial Piston	2000-12,000	1200-3000	90-98	4	1-200	6-50
Radial Piston	3000-13,000	1200-1800	85-95	3	1-200	5-35

The pump is sized according to the necessary flow rate and the speed of the mechanical drive. Slower drive speeds require larger displacement pumps for the same delivery.

PUMP MAINTENANCE

The most common cause of pump failure is dirty, contaminated, or oxidized oil. The pump is more likely to be damaged by rust and corrosion than any other system component. The most essential factor in proper pump maintenance is proper fluid maintenance. Higher operating pressures and closer tolerance of parts require better fluid maintenance; thus, piston pumps are most susceptible to damage.

Pump damage occurs in two ways. Gear and vane pumps are most susceptible to a long-term degradation as the seals are worn by impurities in the oil. Their efficiency and outputs generally decrease gradually. A gradual decrease in pump rate of any pump may occur because of leaking internal parts. If this is suspected, the output flow rate of the pump should be measured under operating pressure and compared to the pump specifications.

Piston pumps are more susceptible to sudden seizing of pump components, which breaks a component and ends pumping immediately. This usually occurs because of a breakdown of the lubricating oil film between pump parts, caused by a reduction of the film strength of the oil or by rust or corrosion on the pump part. This is more likely to occur at higher pressures and operating speeds. For this reason, piston pumps are poor choices for systems in which a sudden loss of fluid flow could result in large losses.

Any time a pump fails, is damaged, or is disassembled, the entire system should be drained of oil and cleaned.

Loud or unusual pump noise indicates a serious problem. The pump should be shut down and inspected immediately. Increased pump noise indicates wear of pump parts, starvation of the pump for oil, or air in the hydraulic fluid. As little as one percent air bubbles in the oil can cause serious pump problems. The most likely cause of pump noise is pump starvation because of clogged filters or entrained oil due to a low oil level in the reservoir. If checking these does not reveal the problem, the pump should be dismantled and inspected. All pump parts must be absolutely clean before reassembly.

Routine pump maintenance consists of keeping the pump exterior clean and maintaining the system oil in a clean condition. Pumps should be routinely inspected for leaks, and attention should be paid to any change in pump sound.

PRESSURE BOOSTERS

A pressure booster consists of a large piston with two smaller rod ends and a series of valves for automatically reciprocating the piston. Low-pressure oil from the system pump drives the large piston. The force produced is applied to the smaller areas of the rod ends to produce an increased pressure in the cylinders containing the rods. The pressure booster is essentially a high-pressure fluid pump driven by lower pressure hydraulic fluid. They are available with pressure ratios of 3:1, 5:1, and 7:1. Pressure boosters are used in a variety of systems to produce high pressure for driving actuators with pumps, piping, and valves that operate at much lower pressures. They are particularly suited for applications in which a piston must extend quickly to meet a load and then produce extremely large forces with a slower extension. A low-pressure pump with a high flow rate extends the piston until it is loaded. Then the pressure booster takes over and produces much greater forces. One such application is in metal punches and presses.

AIR COMPRESSORS

In pneumatic systems, air compressors act in the same capacity as pumps in hydraulic systems. Several types of air compressors may be used. Most are positive-displacement types; however, nonpositive-displacement compressors have become more popular in recent years.

COMPRESSOR CAPACITY

The flow rate of air compressors is usually specified in terms of the free air delivery rate. This is the number of cubic feet of air at standard pressure that the compressor will deliver per minute. Standard pressure is 14.7 psig. The delivery of the compressor at the working pressure must be calculated using the universal gas law equation given in Equation 1.

$$V_2 = \frac{P_1 V_1 T_2}{P_2 T_1} \qquad \text{Equation 1}$$

where: P_1 = Atmospheric pressure.

P_2 = Delivery pressure (absolute).

T_1 = Absolute temperature of intake air (°F + 460°).

T_2 = Absolute temperature of output air (°F + 460°).

V_1 = Free air delivery rate.

V_2 = Delivery rate at working pressure.

All temperatures and pressures must be expressed in absolute terms in this equation. Example A shows the use of Equation 1 in solving a problem.

EXAMPLE A: DELIVERY RATE OF AN AIR COMPRESSOR.

Given: A compressor with a free air delivery of 300 cfm produces a delivery pressure of 150 psig. The input air temperature is 70°F, and the output air temperature is 95°F.

Find: The delivery rate at 150 psig.

Solution: P_1 = 14.7 psia

P_2 = 150 psig + 14.7 psi

P_2 = 164.7 psia

T_1 = 70°F + 460°

T_1 = 530°R (degrees Rankine, absolute)

Example A. Continued.

$T_2 = 95°\text{F} + 460°$

$T_2 = 555°\text{F}$

$V_1 = 300 \text{ cfm}$

$$V_2 = \frac{P_1 V_1 T_2}{P_2 T_1}$$

$$= \frac{(14.7 \text{ psia})(300 \text{ cfm})(555°\text{F})}{(164.7 \text{ psia})(530°\text{R})}$$

$V_2 = 28 \text{ cfm}$

The compressor delivers 28 cfm of air at 150 psig and 95°F.

Most compressors are rated at a specified drive speed, which may not be the actual drive speed in a particular application. If the delivery rate is calculated based on the compressor specifications, the drive speed should be checked and a correction made if the compressor is being driven at a speed different from its specification speed.

RECIPROCATING COMPRESSORS

Most air compressors are the reciprocating type shown in Figure 17. This compressor operates as a positive-displacement piston pump. The cylinders of this model are equipped with large fins for air cooling. Larger models are often water-cooled. Compressors may have a single compression stage or multiple stages (up to four). The compressor shown in Figure 17 is a two-stage compressor — the most common type. In multi-stage compressors, the output from one cylinder is the input for the next. Since air pressure is greater in each successive stage, each piston has a smaller diameter to produce an equal load on the crankshaft. The air travels from one stage to the next through intercoolers. These are finned tubes that dissipate some of the heat of compression before the next compression stage, resulting in more efficient compressor operation. The flywheel carries a fan that forces cooling air across the intercoolers. Water-cooled compressors use water cooling for both the compressor heads and intercoolers. Table 2 lists the pressure capacities of single and multi-stage piston air compressors.

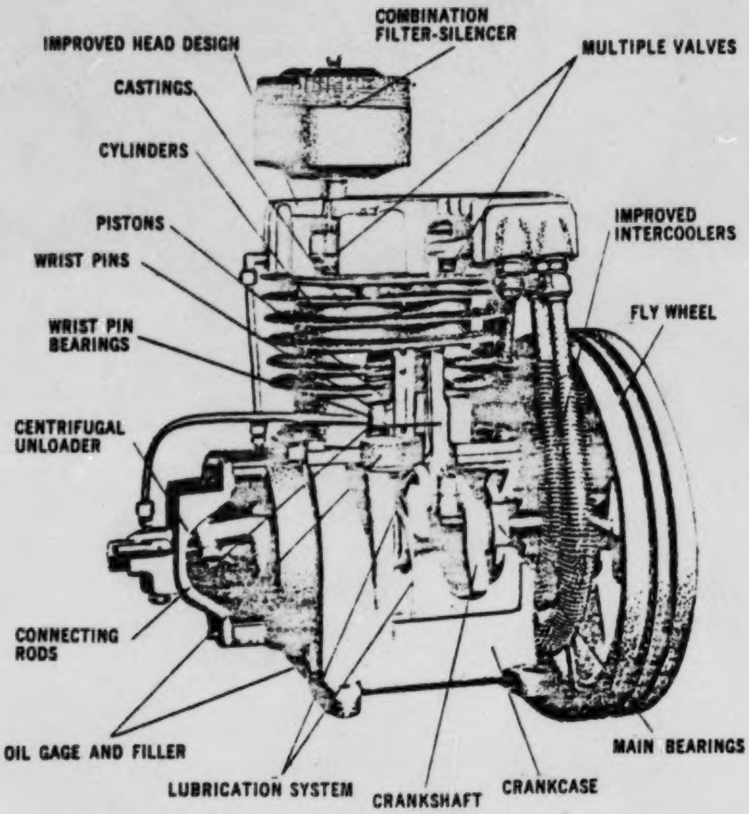

IMPROVED HEAD DESIGN
COMBINATION FILTER-SILENCER
MULTIPLE VALVES
CASTINGS
CYLINDERS
PISTONS
WRIST PINS
IMPROVED INTERCOOLERS
FLY WHEEL
WRIST PIN BEARINGS
CENTRIFUGAL UNLOADER
CONNECTING RODS
OIL GAGE AND FILLER
LUBRICATION SYSTEM
CRANKSHAFT
CRANKCASE
MAIN BEARINGS

Figure 17. Design Features of a Piston-Type Compressor.

TABLE 2. PRESSURE CAPACITY OF RECIPROCATING PISTON AIR COMPRESSORS.

Number of Stages	Pressure Capacity (psig)
1	150
2	500
3	2500
4	5000

Piston compressors cannot start operation against a high pressure. The compressor must be brought up to speed before its output is connected to the high-pressure tank. Figure 18 shows a common method of accomplishing this.

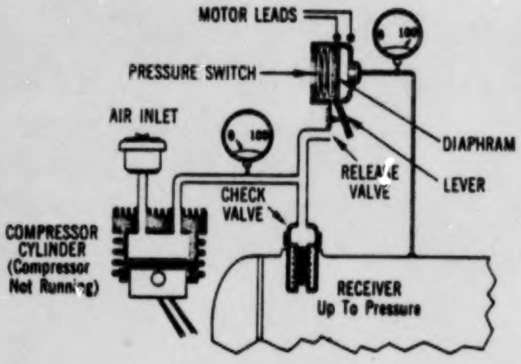

MOTOR LEADS
PRESSURE SWITCH
AIR INLET
DIAPHRAM
RELEASE VALVE
LEVER
CHECK VALVE
COMPRESSOR CYLINDER (Compressor Not Running)
RECEIVER Up To Pressure

Figure 18. Pressure Switch-Type Unloader Control.

The compressor output is connected to the receiver through a check valve and to a pressure-operated release valve. The pressure release valve also operates the compressor motor control. When the pressure in the tank reaches the selected value, the pressure switch turns the motor off and opens the release valve. This releases the high-pressure air trapped between the compressor and tank. The check valve prevents high-pressure air from leaving the tank. When the pressure in the tank drops below another preset value, the pressure switch closes the relief valve and turns the motor on.

Figure 19 shows the centrifugal unloader used on most newer compressors. This unloader is an integral part of the compressor and is more dependable than the pressure switch. With the compressor stopped, the counterweights of the centrifugal device are held in a position near the shaft by springs. This holds the ball valve open and maintains atmospheric pressure at the compressor output. The compressor must approach its operating speed before centrifugal force overcomes the spring force to swing the counterweights away from the shaft and close the ball valve.

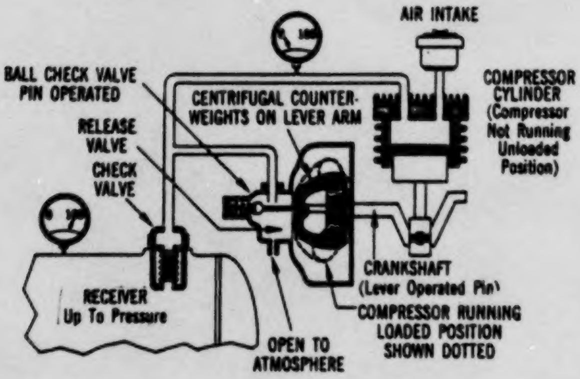

AIR INTAKE
BALL CHECK VALVE PIN OPERATED
CENTRIFUGAL COUNTER-WEIGHTS ON LEVER ARM
COMPRESSOR CYLINDER (Compressor Not Running Unloaded Position)
RELEASE VALVE
CHECK VALVE
RECEIVER Up To Pressure
CRANKSHAFT (Lever Operated Pin)
COMPRESSOR RUNNING LOADED POSITION SHOWN DOTTED
OPEN TO ATMOSPHERE

Figure 19. Centrifugal-Type Unloader Control.

ROTARY COMPRESSORS

Several types of rotary compressors have become popular in recent years. These include both positive-displacement and nonpositive-displacement types. The positive-displacement types include vane and lobe compressors similar in construction to liquid pump types. Vane compressors usually consist of two vane stages in series. Screw compressors operate like screw pumps but employ two power-driven screws instead of a driven shaft with two idlers.

Figure 20 shows a centrifugal compressor of the nonpositive-displacement type. This compressor consists of four centrifugal impellers in series.

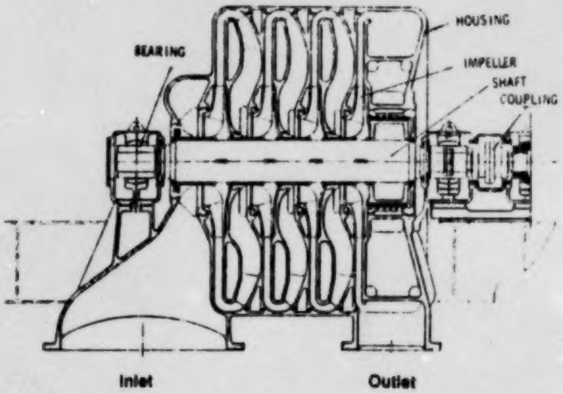


Figure 20. Cutaway View of a Centrifugal Air Compressor.

Atmospheric pressure air enters openings in the center of the first impeller. Centrifugal force moves it out through smaller openings in the edge of the impeller, increasing its pressure. This process is repeated in the other compressor stages. Axial flow centrifugal compressors operate in a similar manner, but employ a single rotating element with several stages of vanes that rotate past fixed vanes in the casing.

Rotary compressors are capable of providing large air volumes at pressures up to about 150 psig.

COMPRESSOR MAINTENANCE

Each compressor type has specific maintenance requirements, but the most important factors in each are the maintenance of clean input air with properly sized, installed, and maintained intake filters and the maintenance of the compressor lubricating oil in a clean state at the proper level. As with pumps, excessive or unusual noise indicates problems.

VACUUM PUMPS

Many pneumatic applications employ vacuums for holding against atmospheric pressure. Vacuum pumps employed in these applications are similar to compressors in construction. The vacuum pump intake is connected to the vacuum tank and the output is open to the atmosphere. Most vacuum pumps are of the vane type, but piston pumps and several other types of rotary compressors are also used.

SUMMARY

Pumps and compressors provide the input power in hydraulic and pneumatic power systems. Most are of the positive-displacement type, providing a constant volumetric displacement with each rotation of the power shaft. The most common and least expensive liquid pump type is the gear pump. Rotary piston pumps are the most expensive and efficient liquid pumps. Vane pump characteristics fall between those of screw and piston pumps.

Most air compressors are of the reciprocating piston type. These are available in multi-stage models that can produce pressures up to 5000 psig. Rotary compressors of both positive-displacement and nonpositive-displacement types have become more popular in recent years.

In all fluid power pumps and compressors, the most important maintenance factors are the cleanliness of the fluid pumped and adequate lubrication. Excessive or unusual noise is usually the first sign of malfunction.

EXERCISES

1. Explain the advantages and disadvantages of positive-displacement pumps and nonpositive-displacement pumps in hydraulic power systems.
2. Explain slippage and volumetric efficiency and how these vary with delivery pressure in the following pump types:
    a. Centrifugal pumps
    b. Gear pumps
    c. Vane pumps
    d. Piston pumps.
3. Explain the effects of pump vibration and noise on the hydraulic power system and how pump noise is used as an indication of pump condition.
4. Choose a major hydraulic pump type for each of the following applications and explain each choice:
    a. A large industrial hydraulic system will not be greatly affected by pump noise. The fluid condition of the system is likely to be poor, and the sudden loss of power will result in damage to the product being manufactured.
    b. A hydraulic pump for aircraft application must provide a smooth delivery at high pressure. Fluid maintenance in the system is excellent.
    c. An industrial processing machine requires fluid flow at variable rates. A small amount of pulsation is acceptable. Fluid maintenance will be good, and it is desirable that sudden pump failure be avoided.
5. Compare the operating efficiencies, available delivery rates, and maximum operating pressures of the following pump types:
    a. Internal gear
    b. External gear
    c. Vane
    d. Radial piston
    e. Axial piston
6. Explain the construction and operation of pressure switch and centrifugal unloaders for reciprocating air compressors.
7. Determine the delivery rate of a compressor at a pressure of 175 psig if the free air capacity is 250 cfm, the input temperature is 85°F, and the output temperature is 100°F.

8. Explain what type of compressor is likely to be chosen for the following applications and why:
   a. Pressures exceeding 200 psig
   b. Large delivery rates at pressures below 150 psig
9. State and explain the most important factor in pump and compressor maintenance.

LABORATORY MATERIALS

Electrical wattmeter
Hydraulic power unit with pressure gauge
Hydraulic fluid flowmeter
Pressure relief valve
Directional control valve
Double-acting hydraulic cylinder arranged to move a load vertically
Load of known weight
One gallon container
Connecting hydraulic hoses
One hose with an open end
English scale
Stopwatch
Air compressor
Tachometer (optional)

LABORATORY PROCEDURES

LABORATORY 1. VOLUMETRIC EFFICIENCY OF A HYDRAULIC PUMP.

1. Connect the following series of hydraulic components on the work surface: power unit output, pressure relief valve, directional control valve, hose with open end. Place the open end of the hose in a hydraulic fluid drain. (Note: Pump must be protected with a pressure relief valve in the hydraulic power unit.)
2. Turn on the hydraulic power unit and operate the DCV to assure proper operation. Be sure hose remains in drain.

3. Set the pressure relief valve to the lowest specified pressure. This must be done with fluid flowing through the output hose.
4. Check the oil level in the reservoir to ensure oil level does not drop below the minimum safe level during the experiment.
5. Use this system and the stopwatch and container to measure the time required for the pump to deliver one gallon of oil.
6. Calculate the flow rate in gallons per minute and record in Data Table 1. Also record the delivery pressure.
7. Repeat this procedure at the pressures specified by the instructor.
8. Remove the pressure relief valve from the system and determine the flow rate for delivery at atmospheric pressure (0 psig). Record this flow rate in the last line of Data Table 1.
9. Determine the volumetric efficiency (%) at each pressure by dividing each flow rate at that pressure by the flow rate at atmospheric pressure and multiplying by 100.
10. Plot volumetric efficiency versus flow rate on a sheet of paper and explain the resulting curve.

LABORATORY 2. OVERALL EFFICIENCY OF A HYDRAULIC SYSTEM.

1. Connect the electrical input of the motor of the hydraulic power unit to a wattmeter. Have the instructor check connections if this instrument is not familiar.
2. Construct the circuit from the Laboratory section of Module FL-02, "Fluid Properties and Characteristics," for the operation of a double-acting hydraulic cylinder. Include the flowmeter in the circuit. Mount cylinder to lift a known weight. This may be accomplished by supporting the cylinder from an overhead support or by bolting a flat metal plate to each end for lifting a weight placed on the upper plate.
3. Operate the circuit with the weight in place to assure proper operation.
4. Measure and record the following in Data Table 2:
    a. Electrical input power during lifting
    b. Delivery pressure
    c. Flow rate
    d. Extension distance

   e. Extension time
   f. Weight lifted

5. Determine the fluid power delivered by the pump by multiplying the delivery pressure times the flow rate in in^3/min (1 gallon = 231 in^3). Convert the power to ft•lb/sec and enter in Data Table 2.
6. Determine the output mechanical power by multiplying the weight of the load times the extension distance in feet and dividing by the extension time in seconds.
7. Convert the electrical input power to ft•lb/sec (1 hp = 746 W) (1 hp = 550 ft•lb/sec).
8. Determine the efficiency of the motor and pump using the electrical input power and the calculated fluid power.
9. Using the electrical input power and the mechanical output power, determind the total system efficiency.
10. Discuss the two efficiencies. Is either the efficiency of the pump?

LABORATORY 3. COMPRESSOR CAPACITY.

1. Determine the rated capacity of the compressor from the compressor data plate. In most cases, this will be stated in cfm at a certain drive rate (rpm). For some compressors, the bore and stroke may be given. In these cases, calculate the volume per revolution in cubic feet. Record the rated delivery in cubic feet per revolution and the method by which it was determined in Data Table 3.
2. Determine the rotational rate of the compressor drive. The most accurate way to accomplish this is to operate the compressor and measure the rotational rate of the flywheel with a tachometer. If a tachometer is not available, read the speed of the compressor drive motor from its specification plate and measure the diameters of the motor pulley and compressor pulley. Using this data, calculate the compressor rotational rate in rpm. Record the rotational rate and the method by which it was determined in Data Table 3.
3. Multiply the rated delivery in cubic feet per revolution by the operating speed in rpm to determine the delivery rate in cfm. Record this in Data Table 3.

4. Determine the delivery of the compressor at the working pressure, as illustrated in Example A. Use the room temperature as the input temperature and assume temperature rises of 20°F and 40°F. Calculate the delivery rate for each of these temperature rises and explain how this illustrates the value of water coolers in the compressor outlet line and intercoolers in multi-stage compressors.

DATA TABLES

DATA TABLE 1. VOLUMETRIC EFFICIENCY OF A HYDRAULIC PUMP.

Delivery Pressure (psig)	Flow Rate (gal/min)	Volumetric Efficiency (%)
Atmospheric		▨

DATA TABLE 2. OVERALL EFFICIENCY OF A HYDRAULIC SYSTEM.

Input electrical power in watts ______________

Delivery pressure ______________

Flow rate ______________

Weight lifted ______________

Extension distance ______________

Extension time ______________

Electrical input power in ft•lb/sec ______________

Fluid power from pump ______________

Output mechanical power ______________

Motor and pump efficiency ______________

System efficiency ______________

Data Table 2. Continued.

Discussion:

DATA TABLE 3. COMPRESSOR CAPACITY.

Compressor Capacity:

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GLOSSARY

Free air delivery: The delivery rate of an air compressor in cubic feet per minute at atmospheric pressure.

Nonpositive-displacement pump: A pump whose delivery rate drops as the delivery pressure increases.

Overall pump efficiency: The percentage of the mechanical input power to the pump that appears as fluidal output power.

Positive-displacement pump: A pump that delivers the same volume of fluid to the pump outlet for each rotation of the drive shaft at all delivery pressures.

Slippage: The flow of oil from the output side of a pump back to the input side through clearance spaces between pump components.

Volumetric efficiency: The ratio of the delivery rate at operating pressure to the delivery rate if no pump slippage occurred; equal to 100% – the percent slippage.

TEST

1. Nonpositive-displacement liquid pumps ...
   a. have only limited application in fluid power systems.
   b. provide an almost constant flow rate within their rated pressure range.
   c. require a pressure relief valve for safe operation.
   d. have high volumetric efficiencies.
   e. None of the above are true.
2. Which hydraulic pump type has the best operating characteristics?
   a. Piston
   b. Vane
   c. Gear
   d. Lobe
   e. Centrifugal
3. Variable-volume hydraulic pumps include which of the following types?
   a. Balanced vane
   b. Internal gear
   c. Axial piston
   d. Both c and d
   e. Only a, c, and d
4. Which of the following hydraulic pumps requires no pressure relief valve for pump protection?
   a. Adjustable axial piston pump
   b. Variable internal gear pump
   c. Pressure-compensated unbalanced vane pump
   d. Pressure-compensated balanced vane pump
   e. Both a and c
   f. Both c and d
5. Gear pumps are popular for many industrial applications because ...
   a. they are inexpensive.
   b. they have a relatively long operating life.
   c. they are least likely to be damaged by contaminated fluid.
   d. they maintain their delivery rate throughout their useful life.
   e. Both a and c are true.
   f. Both a and d are true.

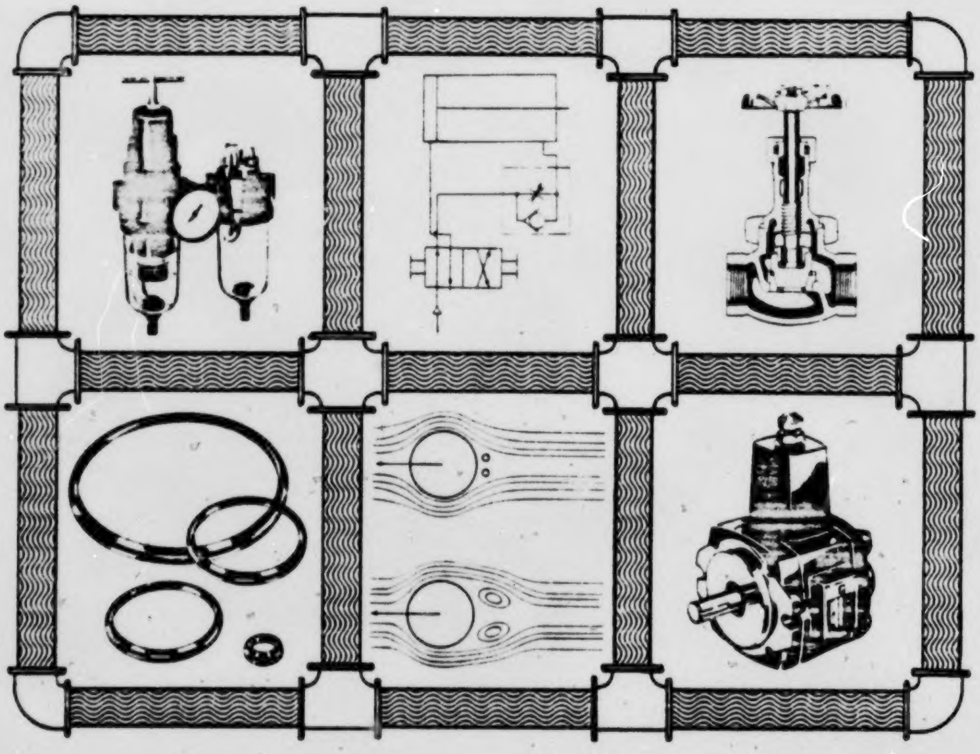
6. Axial piston pumps are the only acceptable hydraulic pump type for applications which require ...
   a. quiet operation.
   b. high-pressure operation.
   c. large capacity flow.
   d. high-speed operation.
   e. Either a or d is true.
7. Vane pump characteristics include ...
   a. higher pressure operation than gear pumps.
   b. maximum available flow rates about the same as gear pumps.
   c. maximum available flow rates about the same as piston pumps.
   d. operating efficiencies as high as many piston pumps.
   e. Both a and d are true.
   f. None of the above are true.
8. The free air capacity of a compressor is 500 cfm. The output air temperature is 90°F, and the input air temperature is 65°F. The output pressure is 150 psig. The delivery rate at the output pressure is ...
   a. 500 cfm.
   b. 35.38 cfm.
   c. 32.23 cfm.
   d. 46.75 cfm.
   e. 59.02 cfm.
9. Which of the following are true of rotary centrifugal compressors?
   a. They are used primarily for applications requiring fairly constant delivery of air at relatively low pressures.
   b. They require an unloading device for beginning compressor operation.
   c. They may be used for high-pressure applications by increasing the number of compressor stages.
   d. Both a and c are true.
   e. All of the above are true.
   f. None of the above are true.
10. The most important factor in both pump and compressor maintenance is ...
   a. keeping the casings and surroundings free from oil and dirt.
   b. maintaining the operating fluid at the proper temperature.
   c. maintaining the fluid in a clean condition.

d. listening for unusual noises.
e. All are equally important.

ENERGY TECHNOLOGY

CONSERVATION AND USE

FLUID POWER



MODULE FL-05

ACTUATORS AND FLUID MOTORS

CORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

Actuators and fluid motors are the fluid power components that convert the power of the working fluid moving under pressure to mechanical power for application to do useful work. The most common type of actuator is the linear motion cylinder. This module discusses the construction, materials used, application, and maintenance of hydraulic and pneumatic cylinders. Several special cylinder types are presented. Rotary actuators are those that provide limited rotational motion in fluid power systems. The basic construction and application of these actuators are also discussed.

Fluid motors provide continuous rotational motion. They are similar in construction and characteristics to fluid pumps. The discussion includes the characteristics of all types of fluid motors commonly used in pneumatic and hydraulic systems.

In the laboratory, the student will operate hydraulic and pneumatic fluid motors and observe their operating characteristics.

PREREQUISITES

The student should have completed Module FL-04, "Pumps and Compressors."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. State the materials commonly used for the cylinder tube, cylinder covers, piston, and rod in hydraulic and pneumatic cylinders.
2. Explain the applications and characteristics of the following methods of attaching the cylinder covers of a hydraulic cylinder:
   a. Tapped cylinder
   b. Tie rod
   c. Tube ring
   d. Threaded tube
3. Explain, with the use of diagrams, the operation of a cylinder cushion.

4. Given the diameter of the piston, the diameter of the rod, the fluid flow rate, and the mechanical load of a double-acting hydraulic cylinder, calculate the following:
   a. Hydraulic pressure during extension
   b. Piston velocity during extension
   c. Cylinder power during extension
   d. Hydraulic pressure during retraction
   e. Piston velocity during retraction
   f. Cylinder power during retraction
5. Explain why air cylinders are usually larger than hydraulic cylinders for producing the same forces.
6. Sketch diagrams and explain the operation of the following actuators:
   a. Tandem cylinders
   b. Duplex cylinders
   c. Double-rod cylinder
   d. Telescopic cylinders
   e. Ram
   f. Rotating cylinder
   g. Vane rotary actuators
   h. Rack and pinion rotary actuators
   i. Helical rod rotary actuator
7. List and explain six common causes of actuator failure.
8. Explain the procedures necessary in the inspection and repair of a damaged cylinder.
9. Compare the operating characteristics of the following types of hydraulic motors:
   a. Gear
   b. Vane
   c. Axial piston
   d. Radial piston
10. Compare the operation of air motors and hydraulic motors.
11. Construct fluid power circuits for the operation of hydraulic and pneumatic fluid motors and compare the characteristics of the two types.

FLUID POWER ACTUATORS

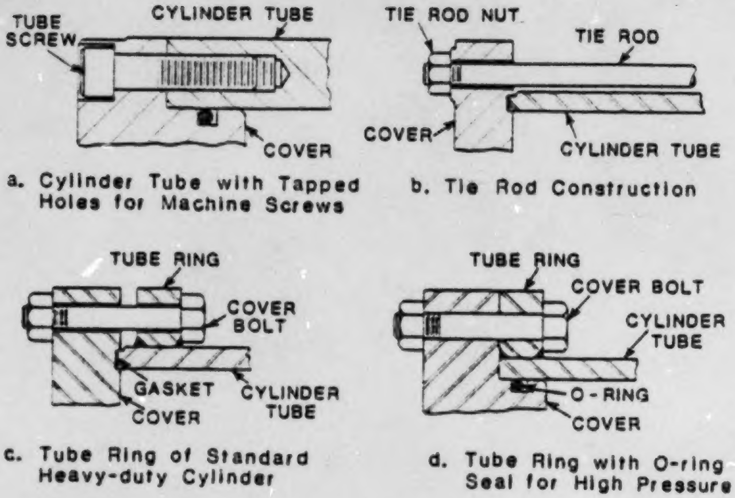
Fluid actuators, the muscles of the fluid power system, convert the power of a flowing, pressurized fluid to the power of mechanical motion. The motion produced may be either linear or rotary. The most common fluid actuator is the linear motion cylinder. In single-acting cylinders, the piston is forced through the extension stroke by fluid pressure and returns by spring action or gravity. Spring return cylinders may have an external spring or an internal spring around the piston rod. In double-acting cylinders, both the extension and retraction strokes are produced by the application of fluid pressure. A variety of cylinder types and sizes are used in both hydraulic and pneumatic power systems.

CONSTRUCTION OF HYDRAULIC CYLINDERS

The cylinder tube of most hydraulic cylinders is made of steel and is usually chrome plated to resist wear and rust. The tubes of low-pressure cylinders are made of cast iron, bronze, brass, or aluminum. The piston is made of cast iron or steel. The piston rod is chrome-plated steel. The ends of the cylinder are called cylinder covers and may be made from high-tensile cast iron, steel bar stock, or cast of forged steel. The cylinder covers contain the inlet and outlet ports and cylinder cushion valves, if applicable. The rod-end cover also contains the piston rod seal.

The cylinder tube and covers can be connected by several means, depending on the cylinder pressure and application. Figure 1 shows four methods of connecting and sealing cylinder covers. In Figure 1a, the ends of the cylinder tube contain holes tapped for machine screws. The screws extend through holes in the cover to hold it in place. The seal is an O-ring in a groove in the cylinder cover. This method is used primarily on shorter cylinders as the process of drilling and tapping holes in the ends of long cylinders is difficult and expensive. One disadvantage of this method is that a screw may break off in the cylinder tube, causing a delay in repairs.

Figure 1b shows the use of tie rods in cylinder construction. The tie rods are steel rods that extend from one cover to the other. The seal is a compression fitting in a slot in the cylinder cover. Pressure is applied to the seal by the tension on the tie rods. This a popular method of cylinder



a. Cylinder Tube with Tapped Holes for Machine Screws

b. Tie Rod Construction

c. Tube Ring of Standard Heavy-duty Cylinder

d. Tube Ring with O-ring Seal for High Pressure

Figure 1. Methods of Mounting Cylinder Covers.

construction because it is the simplest and least expensive to manufacture. Tie rods cannot be used on long, high-pressure cylinders because they will stretch slightly, resulting in a poor seal.

Figure 1c shows the standard tube ring construction used in most heavy-duty mill-type cylinders. A ring is welded to the end of the cylinder tube, and holes are drilled in to match holes in the cylinder cover. The seal is a compression packing, as in tie rod cylinders. Figure 1d is a tube ring connection for a high-pressure cylinder. An O-ring provides a seal, and the contact between the tube ring and cover reduces the changes of distortion of the end of the cylinder tube by overtightening the bolts.

In some smaller cylinders for use at low pressures, the cylinder cover and tube are threaded and simply screw together. An O-ring seal is usually used in this cylinder type.

In many hydraulic cylinders, the impact of the piston on the cylinder cover at full operating speed would damage the cover. Therefore, piston cushions are used to slow the piston at the end of its travel. The piston cushion consists of a tapered extension of the piston rod that enters the outlet port of the cylinder cover, as shown in Figure 2. Exhaust oil passes freely out of the cylinder (1) until the plunger enters the cushion cup (2). The piston is slowed initially by restricted oil flow around the tapered portion of the plunger (3). When the main exhaust port is completely closed, oil must flow out of the cylinder through a smaller opening (4), which can be adjusted to control the rate of deceleration. This produces a back pressure on the piston and slows it further. When oil enters this end of the cylinder, a ball check valve opens to allow free flow of oil to the piston for quick extension (5).

Figure 3 shows the construction details of a typical double-acting hydraulic cylinder with cushions for both the extension and retraction strokes. Piston and rod seals, rod bushing, and wiper rings are also shown. It is important that the cylinder ports be large enough that they do not restrict fluid flow and slow the operation of the cylinder. This is particularly important in double-acting cylinders with a fast retraction stroke and a large diameter rod. In such cylinders, the volume flow rate out of the cylinder may be more than twice the flow rate into the cylinder.

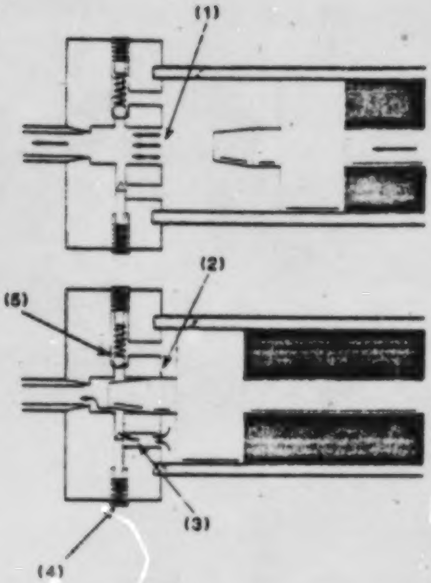


Figure 2. Operation of Cylinder Cushions.

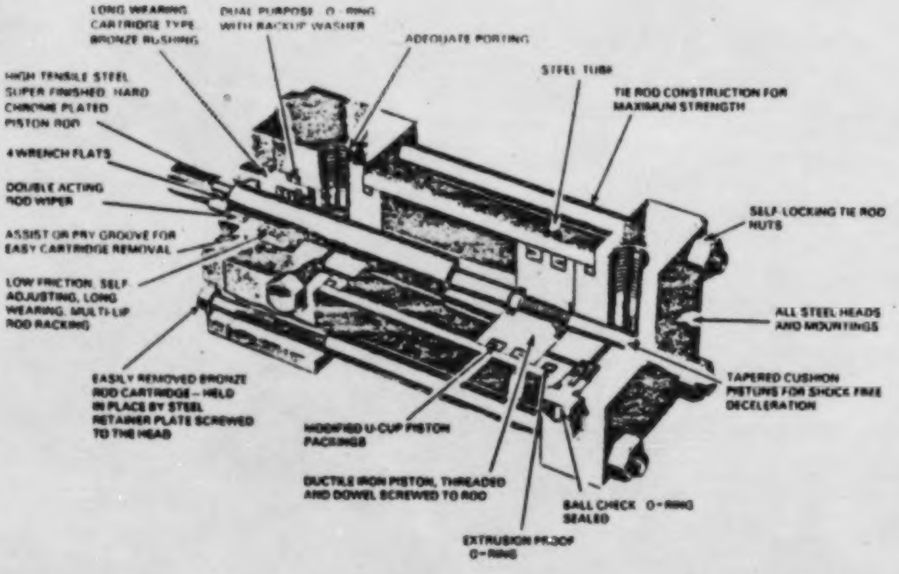

LONG WEARING CARTRIDGE TYPE BRONZE BUSHING
DUAL PURPOSE O-RING WITH BACKUP WASHER
ADEQUATE PORTING
STEEL TUBE
TIE ROD CONSTRUCTION FOR MAXIMUM STRENGTH
HIGH TENSILE STEEL SUPER FINISHED HARD CHROME PLATED PISTON ROD
4 WRENCH FLATS
DOUBLE ACTING ROD WIPER
ASSIST OR PRY GROOVE FOR EASY CARTRIDGE REMOVAL
LOW FRICTION, SELF ADJUSTING, LONG WEARING, MULTI-LIP ROD PACKING
SELF-LOCKING TIE ROD NUTS
ALL STEEL HEADS AND MOUNTINGS
TAPERED CUSHION PISTONS FOR SHOCK FREE DECELERATION
EASILY REMOVED BRONZE ROD CARTRIDGE – HELD IN PLACE BY STEEL RETAINER PLATE SCREWED TO THE HEAD
MODIFIED U-CUP PISTON PACKINGS
DUCTILE IRON PISTON, THREADED AND DOWEL SCREWED TO ROD
BALL CHECK O-RING SEALED
EXTRUSION PROOF O-RING

Figure 3. Double-Acting Cylinder Design.

CYLINDER OPERATING CHARACTERISTICS

The operating speed of a cylinder is determined by the oil delivery rate to the cylinder and the area of the piston. In double-acting cylinders, the retraction stroke is faster because the rod occupies some of the cylinder volume. For calculations of speed and force, the rod area is subtracted from the piston area. Since the maximum force produced by a cylinder is dependent on the effective area on which the pressurized fluid acts, double-acting cylinders have a lower maximum force on retraction than on extension. The pressure in a cylinder during extension and retraction is not the maximum system pressure; this is determined by the mechanical load of the cylinder and its effective area.

Example A illustrates calculations of cylinder operating characteristics.

EXAMPLE A: CALCULATION OF CYLINDER OPERATING CHARACTERISTICS.

Given: A double-acting hydraulic cylinder 2 inches in diameter has an applied load of 2000 lb for both extension and retraction. The piston rod diameter is 1 inch and the pump supplies oil at 10 gallons per minute.

Find: (a) Hydraulic pressure during extension stroke, (b) piston velocity during extension, (c) cylinder power during extension, (d) hydraulic pressure during retraction stroke, (e) piston velocity during retraction, and (f) cylinder power during retraction.

Solution: $A = \frac{\pi d^2}{4}$

Piston area: $A_p = \frac{\pi\ (2\ \text{in})^2}{4}$

$= 3.14\ \text{in}^2$

Rod area: $A_r = \frac{\pi\ (1\ \text{in})^2}{4}$

$= 0.79\ \text{in}^2$

Piston area - rod area: $A_p - A_r = (3.14\ \text{in}^2 - 0.79\ \text{in}^2)$

$= 2.35\ \text{in}^2$

Example A. Continued.

(a) $$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

$$p = \frac{2000\ \text{lb}}{3.14\ \text{in}^2}$$

$$p = 637\ \text{psi}$$

(b) $$\text{Velocity} = \frac{\text{Flow rate}}{\text{Area}}\ (1\ \text{gal} = 231\ \text{in}^3)$$

$$v = \frac{(20\ \text{gal/min})\left(\frac{231\ \text{in}^3}{1\ \text{gal}}\right)\left(\frac{1\ \text{min}}{60\ \text{sec}}\right)}{3.14\ \text{in}^2}$$

$$= \frac{77\ \text{in}^3/\text{sec}}{3.14\ \text{in}^2}$$

$$= (24.5\ \text{in/sec})\left(\frac{1\ \text{ft}}{12\ \text{in}}\right)$$

$$v = 2.04\ \text{ft/sec}$$

(c) Power = Force x Velocity (1 hp = 500 ft·lb/sec)

$$P = (2000\ \text{lb})(2.04\ \text{ft/sec})$$

$$= (4080\ \text{ft}\cdot\text{lb/sec})\left(\frac{1\ \text{hp}}{550\ \text{ft}\cdot\text{lb/sec}}\right)$$

$$P = 7.42\ \text{hp}$$

or

Power = Pressure x Flow rate

$$P = (637\ \text{lb/in}^2)(77\ \text{in}^3/\text{sec})$$

$$= (49{,}049\ \text{in}\cdot\text{lb/sec})(1\ \text{ft}/12\ \text{in})$$

$$= (4087\ \text{ft}\cdot\text{lb/sec})$$

$P = 7.43$ hp (slight difference is due to round off)

(d) $$p = \frac{F}{A}$$

$$= \frac{2000\ \text{lb}}{2.35\ \text{in}^2}$$

$$p = 851\ \text{psi}$$

(e) $$v = \frac{Q}{A}$$

$$= \left(\frac{77\ \text{in}^3/\text{sec}}{2.35\ \text{in}}\right)\left(\frac{1\ \text{ft}}{12\ \text{in}}\right)$$

$$v = 2.75\ \text{ft/sec}$$

Example A. Continued.

(f) $P = F \times V$

$$= (2000\ \text{lb})(2.75\ \text{ft/sec})\left(\frac{1\ \text{hp}}{550\ \text{ft}\cdot\text{lb/sec}}\right)$$

$P = 10$ hp

The retraction stoke has a higher velocity than the extension stroke and a higher power since the load is the same and is moving faster.

CONSTRUCTION OF AIR CYLINDERS

Air cylinders are similar in construction to hydraulic cylinders. However, since most air cylinders operate at pressures of around 100 psig, they are not constructed as heavily as hydraulic cylinders. Most are made of aluminum or other nonferrous metals to reduce weight and withstand the corrosive properties of air. Seals are designed to withstand the damaging properties of air but need not contain the high pressures of most hydraulic cylinders. Air pistons for the application of large forces must have large areas because of the relatively low operating pressures. They are available in diameters up to 30 inches.

MOUNTING AND APPLICATION OF CYLINDERS

Both hydraulic and pneumatic cylinders are available with a variety of cylinder mountings. Figure 4 illustrates the more common types of cylinder mounts. In most cases, the rod is threaded, but other types of rod connections are available. One of the major causes of cylinder damage is side thrust on the piston due to misalignment of the mounts. This can be eliminated by mounting each end of the cylinder in a universal mount.

The choice of a cylinder for a particular application depends on several factors. Obviously, the cylinder must be able to withstand the maximum system pressure and must have the appropriate diameter and stroke for the application. It should also be selected with seals and finishes that are compatible with the expected fluid conditions. If the cylinder is to be used only occasionally or at reduced load, a light-duty, less expensive model may serve the purpose. For frequent operation at full load or for extended service life, heavy-duty cylinders should be chosen. In many systems, the down time resulting from component failure is extremely important. Cylinders in such systems should be chosen for dependability, ease of servicing, and availability of replacement parts. In applications where the extended piston rod is subject to dust, dirt, or other contamination, it should be protected by a rod boot (Figure 5).

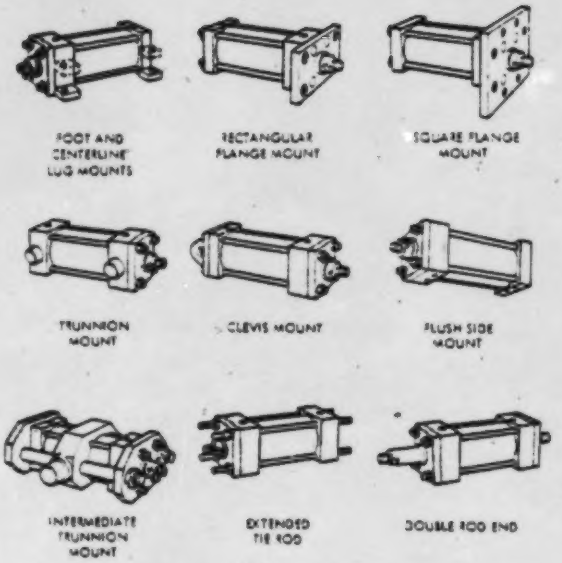

FOOT AND CENTERLINE LUG MOUNTS
RECTANGULAR FLANGE MOUNT
SQUARE FLANGE MOUNT
TRUNNION MOUNT
CLEVIS MOUNT
FLUSH SIDE MOUNT
INTERMEDIATE TRUNNION MOUNT
EXTENDED TIE ROD
DOUBLE ROD END

Figure 4. Various Cylinder Mountings.

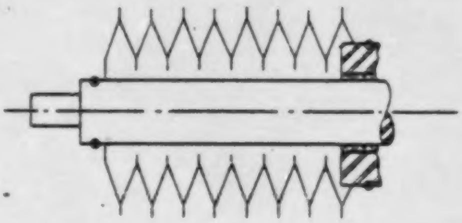


Figure 5. Cross-Sectional Sketch of a Rod Boot.

SPECIAL CYLINDER TYPES

Several special cylinder types have been developed for some applications and conditions. The tandem cylinder (Figure 6) is used when space limitations prevent the use of a single cylinder large enough to produce the necessary force. It consists of two cylinders and pistons with one common rod and produces twice the force of a single piston. Tandem cylinders are used in both hydraulic and pneumatic systems, but air cylinders are more common because of the large areas necessary to produce large forces with lower pressure pneumatic systems.

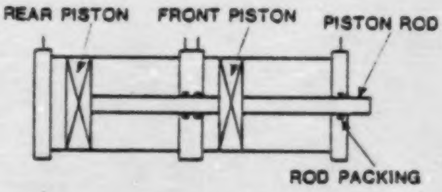

REAR PISTON
FRONT PISTON
PISTON ROD
ROD PACKING

Figure 6. Tandem Cylinder.

Figure 7 shows a duplex cylinder, which is actually two separate cylinders mounted in line with concentric but separate rods. Either cylinder can be actuated separately.

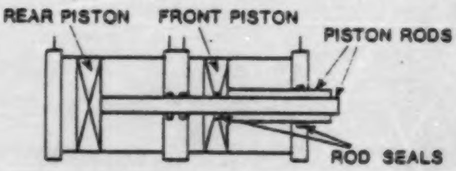

REAR PISTON
FRONT PISTON
PISTON RODS
ROD SEALS

Figure 7. Duplex Cylinder.

Figure 8 shows a telescopic cylinder for achieving long extensions with a compact size when retracted. These cylinders are commonly used for lifting operations in both hydraulic and pneumatic systems.

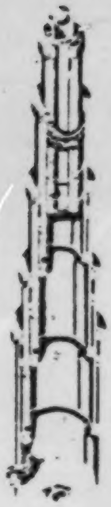


Figure 8. Telescopic Cylinder.

Rams are single-acting cylinders with a one-piece rod and piston with a constant diameter. They are usually used in high-pressure hydraulic systems to produce extremely large forces. A double-rod cylinder is one with a single piston and a rod extending through each cylinder cover for moving two loads at a time.

Figure 9 shows the components of a rotating cylinder. This cylinder does not produce rotational motion but is, rather, a means of translating a rotating shaft along its axis of rotation. Since rotation of the piston in the cylinder would endanger the piston and rod seals, both the piston and the cylinder rotate with the spinning shaft. A steel drive pin extends through a hole in the piston and into each cylinder cover. This prevents piston rotation and, in some models, can be used to transmit rotational power. Oil is channeled to and from the cylinder by a stationary oil shaft on the end of the cylinder opposite the piston rod. Rotating cylinders are available for either oil or air service. Some models have an opening through the center with oil or air feeds in a stationary outer casing. This type is commonly used to operate power chucks on lathes and milling machines.

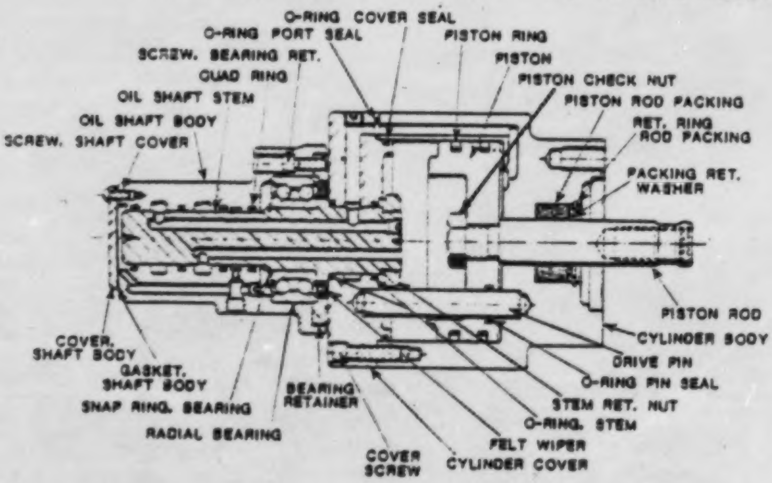

O-RING COVER SEAL
O-RING PORT SEAL
PISTON RING
SCREW. BEARING RET.
PISTON
QUAD RING
PISTON CHECK NUT
OIL SHAFT STEM
PISTON ROD PACKING
OIL SHAFT BODY
RET. RING
ROD PACKING
SCREW. SHAFT COVER
PACKING RET.
WASHER
PISTON ROD
CYLINDER BODY
COVER.
SHAFT BODY
DRIVE PIN
GASKET.
SHAFT BODY
O-RING PIN SEAL
BEARING
RETAINER
STEM RET. NUT
SNAP RING. BEARING
O-RING. STEM
RADIAL BEARING
FELT WIPER
COVER
SCREW
CYLINDER COVER

Figure 9. Hydraulic Rotating Cylinder.

ROTARY ACTUATORS

Rotary actuators are devices for producing limited rotational motion. Figure 10 shows the simplest rotary actuator. It consists of a cylinder containing a stationary barrier and a shaft that is rotated by a vane. Fluid pressure on one side of the vane causes the rotation. A single-vane rotary actuator has a rotation of 280°. Double-vane models have two barriers and a rod with two vanes. They produce twice the output torque but have a rotational angle of only 100°. Vane-type rotary actuators can be used in both hydraulic and pneumatic systems but are more common in hydraulic applications.

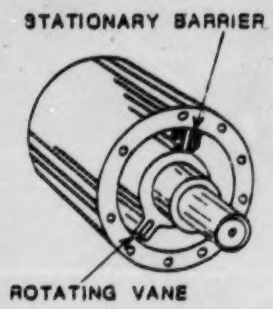

STATIONARY BARRIER
ROTATING VANE

Figure 10. Limited Rotation Hydraulic Actuator.

The rack and pinion rotary actuator, available for either oil or air, consists of two cylinders with pistons attached to rack gears (Figure 11). The linear motion of the racks is transformed to rotational motion of the pinion and output shaft. Pressure applied to one cylinder produces rotary motion in one direction; pressure applied to the other cylinder reverses the rotation. Typically, this type of rotary actuator provides rotation through 360°.

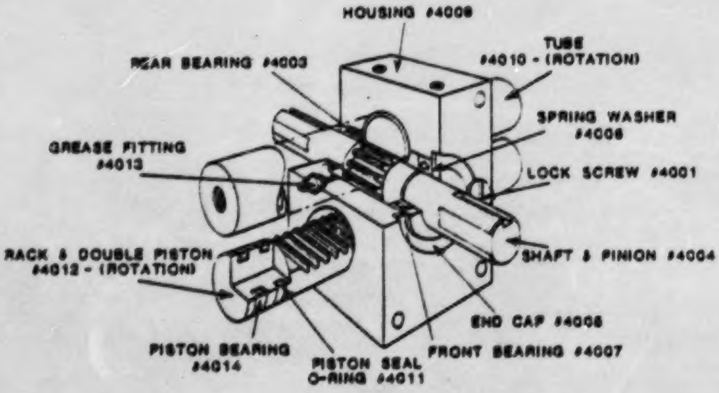

HOUSING #4009
REAR BEARING #4003
TUBE #4010 - (ROTATION)
SPRING WASHER #4006
GREASE FITTING #4013
LOCK SCREW #4001
RACK & DOUBLE PISTON #4012 - (ROTATION)
SHAFT & PINION #4004
END CAP #4005
PISTON BEARING #4014
PISTON SEAL O-RING #4011
FRONT BEARING #4007

Figure 11. Rack and Pinion Drive Rotary Actuator.

Figure 12 is a hydraulic rotary actuator using a helical rod and a piston with a matching hole in the center. Rotation of the piston is prevented by a pair of guide rods extending through the piston and anchoring in each cylinder cover. Linear motion of the piston causes the output shaft to rotate. This type of rotary actuator is complex and expensive, but it allows fine control, can be stopped at any point, and provides positive holding even if power is lost.

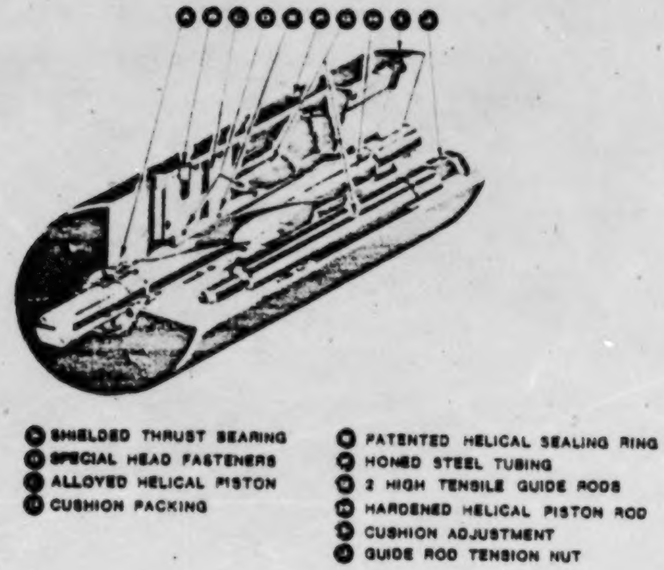

SHIELDED THRUST BEARING
SPECIAL HEAD FASTENERS
ALLOYED HELICAL PISTON
CUSHION PACKING
PATENTED HELICAL SEALING RING
HONED STEEL TUBING
2 HIGH TENSILE GUIDE RODS
HARDENED HELICAL PISTON ROD
CUSHION ADJUSTMENT
GUIDE ROD TENSION NUT

Figure 12. Rotary Actuator with Helical Piston and Rod.

CAUSES OF CYLINDER FAILURE

With proper installation, application, and cylinder and fluid maintenance, fluid power actuators will give long and dependable service. The following are the most common causes of cylinder failure:

- Dirt: The greatest cause of cylinder failure is dirt in the working parts. Particles may enter through the rod seals but are more likely to be carried into the cylinder by dirty oil or air. Dirt can destroy the seal materials or score the cylinder, piston, or rod. This can cause leaks and, if severe enough, can cause the piston to seize.
- Heat: Excessive heat causes deterioration of packings and seals. Cylinders should never be operated above the temperature limits of the seal materials. For most common cylinders, the upper limit is 140°F, although special materials for up to 500°F are now available.
- Misapplication: A large percentage of cylinder failures can be attributed to misapplication of the cylinder. Cylinders with cast iron covers should not be used in applications involving high impact shocks

or eccentric loads. Light and medium-duty cylinders used in heavy-duty applications will often fail in a few days.

- Misalignment: Side thrusts or eccentric loads will cause excessive wear on one side of the piston rod and cylinder tube. This can destroy seals and result in scored parts, bent rods, and cracked cylinder covers.
- Improper mounting: If the cylinder is not securely and properly mounted, it may not able to withstand the forces produced by normal operation. It can break away from its mount, causing damage to both itself and surrounding equipment. If the mount becomes loose, the cylinder is much more susceptible to misalignment.
- Improper lubrication: In air cylinders, failure is often the result of improper lubrication. The proper maintenance of air-line lubricators is the most essential element in pneumatic cylinder maintenance.

CYLINDER MAINTENANCE

All cylinders should be checked routinely and removed from service at the first sign of problems. Continued operation will usually result in more serious damage in a very short time. The following steps should be taken in inspecting and repairing a defective cylinder:

1. Remove the cylinder from the system and disassemble it in a clean location. Cylinders should not be disassembled while in place in the system unless absolutely necessary.
2. Clean each part. If the cylinder is not to be reassembled immediately, coat each metal part with a good preservative and store in a protected container.
3. Check piston rod for straightness. If it is bent, it must be straightened or replaced.
4. Examine the rod for any stratches, indentations, or blemishes. Any damage that can be detected is serious enough to require correction. Small, shallow blemishes and scratches can be removed with emery cloth. If grinding the rod is necessary, it should be chrome plated to restore its original diameter and provide protection.
5. Examine cover and cushion bushings for wear and finish. Replace any parts that show the slightest defects.

6. Examine the cylinder tube for scratches. Replace or replate damaged tubes.
7. It is strongly advised that all seals and packings be replaced. Only those seal materials that are in "new" condition should be reused. A light coating of grease on packings will often make assembly easier.
8. If a piston with rings is to be replaced, the piston should be attached to the rod and ground concentrically with it for a close fit in the cylinder.
9. Cylinders with foot-mounted covers should be assembled on a surface plate, and all mounting pads should make full contact with the surface. Otherwise, the piston may bind during operation.
10. Tighten all cover bolts evenly, but do not overtighten. Compression packings require considerably more tension than O-ring seals.
11. Operate the cylinder at reduced pressure and check for proper operation. Then operate at full pressure and check for any leaks. Check for internal leaks by pressurizing one cylinder port with the other open to atmosphere.

FLUID MOTORS

Fluid motors provide continous shaft rotation. Essentially, they are pumps operated in reverse. Module FL-04, "Pumps and Compressors," contains diagrams of major pump and motor types. The basic designs are the same. The differences in construction details are primarily the result of different configurations of forces on working components.

HYDRAULIC MOTOR TYPES

Hydraulic motors fall into three major classes: gear, vane, and piston.

Internal and external gear motors are available in configurations essentially the same as pumps and having the same limitations and characteristics. However, pressure channels in the external gear pump apply full pressure to the gears 180° apart to reduce side thrust. Screw motors are similar in all details to screw pumps and offer the same characteristics.

Vane motors are constructed similar to balanced vane pumps. Centrifugal force cannot be used to hold the vanes in contact with the pressure ring for motor starting. Vanes can be held in place by springs or by high-pressure fluid channels leading to the inner portions of the vane slots. Unbalanced vane motors can be built for variable speed operation, but these are seldom used because other variable speed motors give superior performance.

Axial piston motors are available in bent-axis and in-line designs. Variable speed motors are controlled in the same way as variable output pumps. In-line models with adjustable swash plates can be reversed by changing the angle of the swash plate. Like axial piston pumps, axial piston motors provide the highest speeds and best performance.

Radial piston motors are the only type that are greatly different from their motor counterparts. They are designed for low-speed, high-torque applications. Figure 13 shows a Staffa piston motor consisting of five radial pistons connected to a central camshaft. It is designed to operate smoothly and efficiently at speeds as low as 3 rpm. A hole in the top of each piston allows high-pressure oil to flow between the closely fitting pistons, connecting rods, and camshaft. Since all parts ride on a cushion of oil, friction and wear are almost eliminated. These motors are the most efficient available with overall efficiencies as high as 98%.

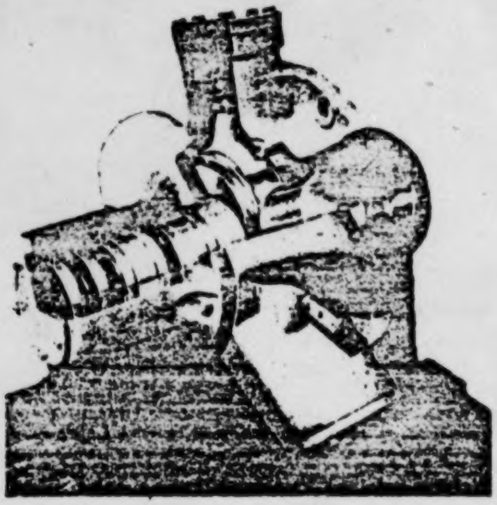


Figure 13. Low-Speed, High-Torque Motor.

Figure 14 is a diagram of another type of low-speed radial piston motor often used in the hubs of vehicles, It has a stationary hub and a rotating outer rim. An even number of opposing pistons are located in the fixed hub. They apply forces to a specially shaped cam ring through rollers that reduce friction. Slide guides ride in a slot in the cam ring to absorb any side thrusts. Oil is directed to and from the proper cylinders by a rotary oil distribution valve that rotates with the cam ring and rim. The direction of rotation can be reversed by changing the oil flow, and throttling the flow provides speed control. Free wheeling is accomplished by pressurizing the case and retracting the pistons and rollers.

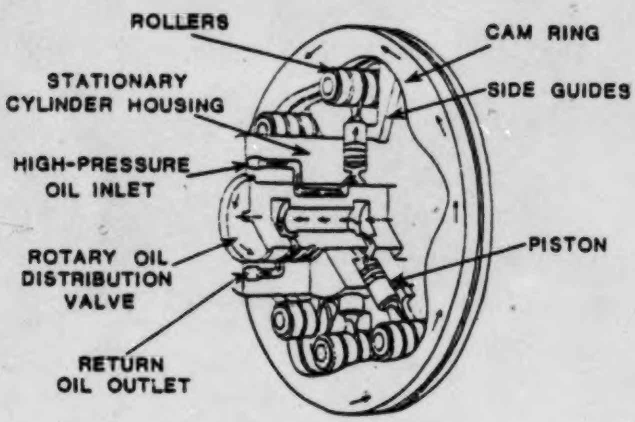

ROLLERS
CAM RING
STATIONARY CYLINDER HOUSING
SIDE GUIDES
HIGH-PRESSURE OIL INLET
PISTON
ROTARY OIL DISTRIBUTION VALVE
RETURN OIL OUTLET

Figure 14. Operating Principles of Low-Speed, High-Torque Motor.

HYDRAULIC MOTOR PERFORMANCE

The similarity of hydraulic motors and pumps leads to similar operating characteristics. Table 1 lists the characteristics of major hydraulic motor types. (Compare these to pump characteristics in Module FL-04, "Pumps and Compressors.")

TABLE 1. HYDRAULIC MOTOR CHARACTERISTICS.

Motor Type	Maximum Pressure (psig)	Maximum Speed (rpm)	Maximum Flow Rate (gpm)	Overall Efficiency (%)
Gear	2,000	2,400	150	70 - 75
Vane	2,500	4,000	250	75 - 85
Axial piston	5,000	12,000	450	85 - 95
Radial piston	3,000	500	180	90 - 98

Figure 15 shows the performance curves of a variable speed axial piston motor. Other hydraulic motor types have similar curves with different specific values. As with pumps, volumetric efficiency is highest at lower pressures and higher speeds. Torque produced depends on the operating pressure of the motor — not on motor speed. Motor speed increases in direct proportion to oil flow rate. Thus, the speeds of fixed-displacement hydraulic motors can be controlled by regulating the oil flow rate to the motor.

AIR MOTORS

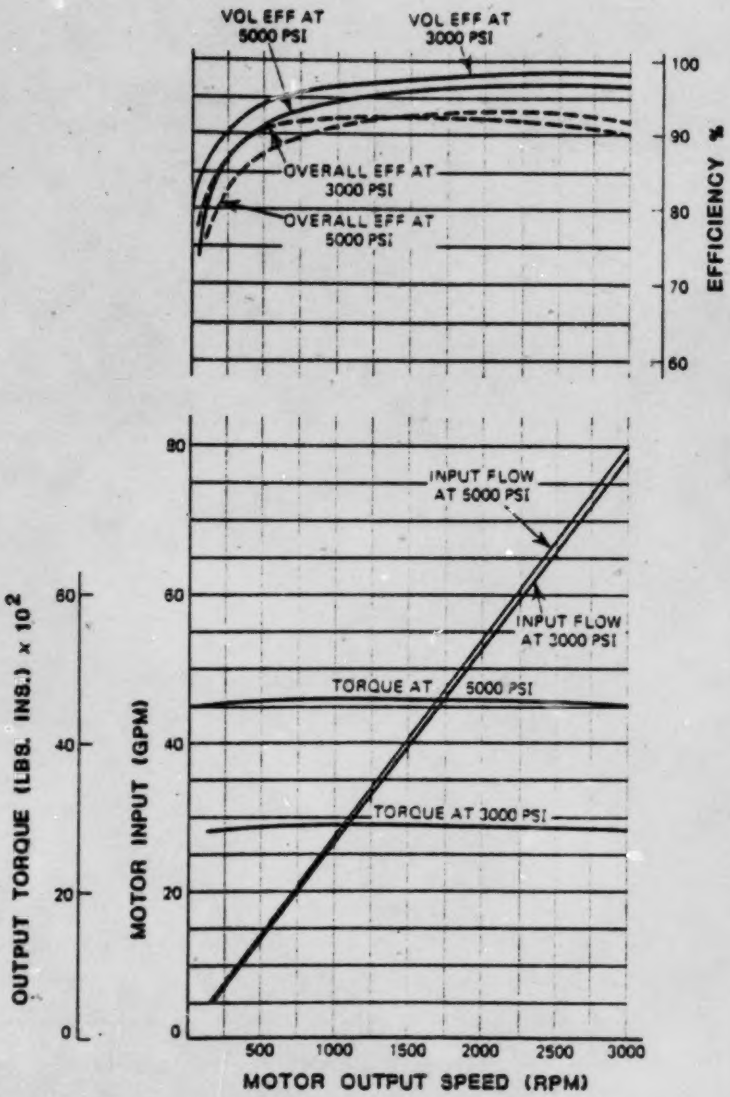


Figure 15. Performance Curves for 6-in^3 Variable Displacement Motor.

Air motors have the same general designs as hydraulic motors. Several types of gear motors may be used, but they are not popular. Vane-type air motors are available in several designs. Most are of the unbalanced type. Some are designed for rotation in only one direction and others may be reversed by changing the direction of airflow. Axial piston and radial piston air motors are similar in design and performance to those types of hydraulic motors.

Since air is a compressible fluid, air motor characteristic curves differ considerably from those of similar hydraulic motors. Figure 18 shows typical performance curves for an axial piston air motor similar in design to the hydraulic motor. These curves show the variations in torque and power delivered as speed varies at three constant delivery pressures. Unlike hydraulic motors, the speed of an air motor depends on the load driven by the motor. At low speeds, air motors produce maximum torque but do not deliver much power. As speed increases, torque decreases.

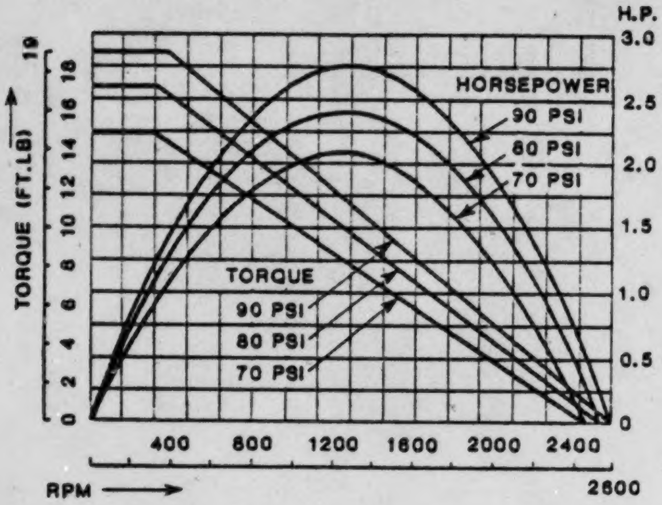


Figure 16. Typical Torque-Speed and Horsepower-Speed Curves for Axial Piston-Type Air Motor.

Mechanical power delivered rises with motor speed to a maximum near the midpoint of the motor speed range. Light loading of the motor results in high speeds with little torque and little power output. Air motor speed can be varied by changing the flow rate but cannot be controlled exactly as can that of hydraulic motors because air motor speed is dependent on load.

MAINTENANCE OF FLUID MOTORS

Fluid power motors are subject to the same maintenance problems and requirements as pumps. As with pumps, the most serious problems arise because of impurities in the working fluid. Unusual noise is often the first indication of malfunction.

SUMMARY

Fluid power is converted to mechanical power by actuators and fluid motors. The most common type of actuator is the linear motion cylinder. These cylinders are available in a wide variety of configurations for both hydraulic and pneumatic applications. Their major components include a cylinder tube with two cylinder covers, a piston, a piston rod, and appropriate packings and seals. The selection of a cylinder for a particular application depends on the force the cylinder must produce and the stresses it will encounter during normal operation. Rotary actuators provide limited rotation and are usually of the vane or rack and pinion type. The most important consideration in cylinder maintenance is the cleanliness of the working fluid, but proper installation is also essential for good performance and extended life.

Fluid motors are constructed in much the same way as fluid pumps and have similar operating characteristics. The speed of hydraulic motors is completely controlled by the oil flow rate and is independent of the motor load. The speed of air motors can be adjusted by changing the air flow rate, but their speed varies with the mechanical load on the motor. Maintenance considerations for fluid motors are the same as for pumps.

EXERCISES

1. A double-acting hydraulic cylinder has a piston 4 inches in diameter. The area of the rod is one-half the area of the piston. The mechanical load for both extension and retraction is 3500 lb and the fluid flow rate is 20 gpm. The stroke of the piston is 15 inches. Find the following:
   a. Pressure during extension
   b. Pressure during retraction
   c. Extension time
   d. Retraction time
   e. Power during extension
   f. Power during retraction
2. A double-acting hydraulic cylinder has a diameter of 5 inches and a rod diameter of 2.5 inches. The cylinder must retract a distance of 1 foot against a force of 6000 lb in 1.5 seconds. Find the following:
   a. Pressure required (assume no losses)
   b. Volume flow rate of pump
   c. Power of pump
   d. Maximum extension force with the same pressure
   e. Extension time
3. List the advantages of fluid motors over electric motors. Consult the library for further information.
4. Compare the operating characteristics of hydraulic motors and pneumatic motors.

5. Choose a hydraulic motor type for each of the following applications and explain each choice:
    a. An industrial motor must develop 300 hp at a constant speed of 3600 rpm. The least expensive motor with this capability is desired.
    b. A motor must operate at variable speeds up to 10,000 rpm and must be reversible.
    c. A motor must develop high torque at less than 50 rpm.
    d. The least expensive motor is desired for an application requiring 30 hp at 1800 rpm. Fluid maintenance is likely to be poor.
6. Explain the six most common causes of cylinder failure.

LABORATORY MATERIALS

Hydraulic power unit
Hydraulic pressure relief valve
Hydraulic directional control valve
Pressure-compensated flow control valve
Reversible fluid motor
Hydraulic flowmeter
Hydraulic pressure gauge
Connecting hydraulic hoses
Pneumatic power unit
Two pneumatic directional control valves
Air pilot valve
Needle valve
Air motor
Compressed air flowmeter
Air pressure gauge
Muffler
Connecting pneumatic hoses
Motor loading device consisting of a steel disk attached to the motor shaft and riding between two disk brake pucks in a support bolted to the work surface (adjustable tension)
Tachometer or strobe to measure motor speed

LABORATORY 1. OPERATION OF A HYDRAULIC MOTOR.

1. Construct the circuit shown in Figure 17.
2. Connect the loading device to the hydraulic motor shaft. Set for light tension.
3. Have instructor check the setup.
4. Turn on the hydraulic power unit and set the pressure relief valve to the desired pressure.
5. Operate the circuit with light tension on the loading device. Vary the setting of the flow control valve and verify motor speed control. Operate the DCV and verify motor stopping and reversal.

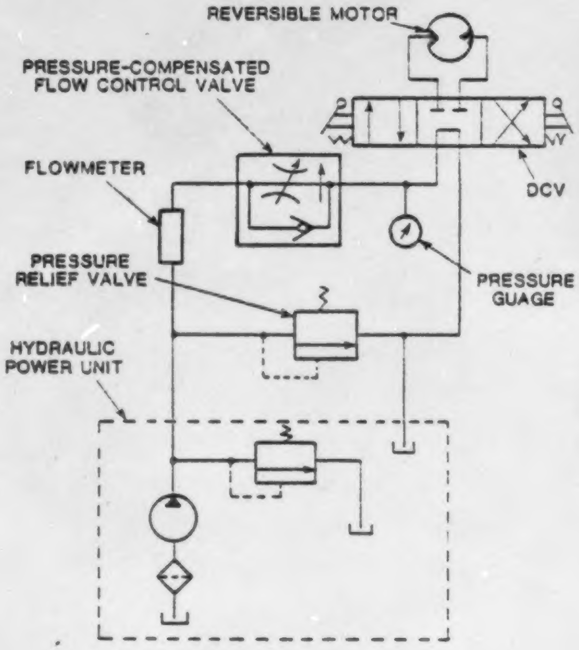


Figure 17. Hydraulic Motor Circuit.

6. Turn the motor on and adjust the flow control valve to produce the first desired flow or motor speed as specified by the instructor. The loading device should be set for very light tension.
7. Measure the flow rate, motor speed, and fluid pressure at the motor, and record in the low tension line of Data Table 1.
8. Increase the tension on the loading device to bring the pressure at the motor to one-third the maximum system pressure.
9. Measure the flow rate, motor speed, and fluid pressure, and record in the medium tension line of Data Table 1.
10. Increase the tension of the loading device to produce two-thirds the maximum system pressure at the motor. Repeat the above measurements and record in the high tension line of Data Table 1.
11. Set the flow control to two other flow rates or motor speeds as specified by the instructor and repeat Steps 7 through 10 for each.
12. Describe the effects of increased motor load on flow rate, motor speed, and fluid pressure at the motor.

LABORATORY 2. OPERATION OF AN AIR MOTOR.

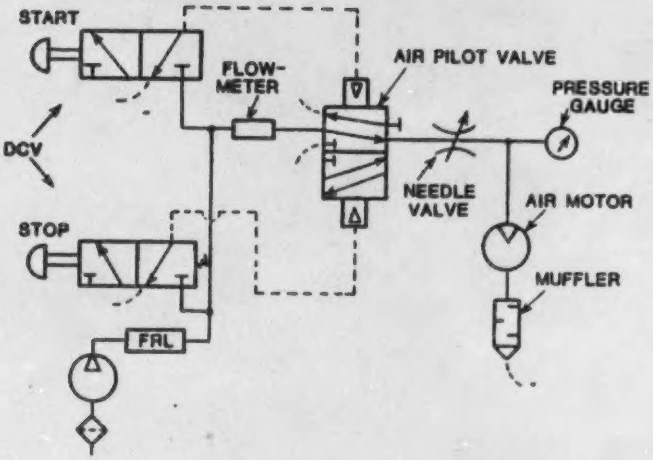


Figure 18. Air Motor Circuit.

1. Construct the fluid power circuit shown in Figure 18.
2. Connect the loading device to the air motor shaft. Set for light tension.
3. Have instructor check the setup.
4. Close the needle valve for minimum flow and turn on the pneumatic power unit. Set the regulator for the desired pressure.
5. Operate the circuit with light tension on the loading device. Open the needle valve to achieve motor rotation. Verify proper operation of start and stop controls.
6. Turn on the motor and adjust the needle valve to produce the first desired flow rate as specified by the instructor. The loading device should be set for light tension.
7. Measure the flow rate, motor speed, and fluid pressure at the motor, and record in the low tension line of Data Table 2.
8. Increase the tension of the loading device to increase the pressure at the motor to one-third the maximum pressure.
9. Measure the flow rate, motor speed, and fluid pressure, and record in the medium pressure line of Data Table 2.
10. Increase the tension of the loading device to produce two-thirds the maximum pressure. Repeat the above measurements and record in the high tension line of Data Table 2.

11. Set the needle valve for two other flow rates as specified by the instructor and repeat Steps 7 through 10 for each. Needle valve settings should be made with light tension on the loading device.
12. Describe the effects of increased motor load on flow rate, motor speed, and pressure at the motor.
13. Compare the characteristics of the hydraulic motors and the air motor.

DATA TABLES

DATA TABLE 1. OPERATION OF A HYDRAULIC MOTOR.

Flow Rate (gpm)	Motor Load (relative)	Motor Speed (rpm)	Fluid Pressure (psig)
	Low		
	Medium		
	High		
	Low		
	Medium		
	High		
	Low		
	Medium		
	High		

DATA TABLE 2. OPERATION OF AN AIR MOTOR.

Flow Rate (cfm)	Motor Load (relative)	Motor Speed (rpm)	Fluid Pressure (psig)
	Low		
	Medium		
	High		
	Low		
	Medium		
	High		
	Low		
	Medium		
	High		

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GLOSSARY

Actuator: A fluid power component that converts fluidal power to mechanical power, either linear motion or limited rotation.

Cylinder cover: The closures on the ends of the cylinder tube.

Cylinder tube: The tube in which the piston moves.

Double-rod cylinder: A cylinder with a piston rod extending out through each cylinder cover.

Duplex cylinder: Two cylinders mounted in line but acting separately with one piston rod inside the other.

Fluid motor: A fluid power device that converts fluidal power to continuous rotational mechanical power.

Piston cushion: A device for decelerating the piston and reducing mechanical shock to the cylinder.

Rotary actuator: An actuator that produces limited rotary motion.

Rotating cylinder: A cylinder that rotates as part of a shaft and imparts linear motion to the shaft along its axis of rotation.

Tandem cylinder: Two cylinders in series with their pistons acting on a single rod.

1. Chrome-plated steel is commonly used for which of the following?
   a. Pneumatic cylinder tubes
   b. Hydraulic cylinder tubes
   c. Piston rods
   d. Hydraulic pistons
   e. Both b and c
   f. Only b, c, and d
2. Which of the following cannot be used to produce rotary motion?
   a. Linear motion cylinder
   b. Vane rotary actuator
   c. Helical rod actuator
   d. Rotating cylinder
   e. None of the above (All can produce rotary motion.)
3. The speed of a hydraulic motor depends on ...
   a. the fluid pressure.
   b. the fluid flow rate.
   c. the mechanical load.
   d. Both b and c are true.
   e. All of the above are true.
4. Which of the following fluid motors can be reversed without changing the direction of fluid flow?
   a. Axial piston air motors
   b. Radial piston hydraulic motors
   c. Unbalanced vane air motors
   d. Balanced vane hydraulic motors
   e. None of the above
5. The most efficient type of fluid motor is the ...
   a. radial piston motor.
   b. axial piston motor.
   c. gear motor.
   d. screw motor.
   e. Both b and d are true.

6. Tie rod construction is popular for hydraulic cylinders because ...
   a. tie rods make long cylinders more rigid.
   b. they put more pressure on the O-rings for a better seal.
   c. they are less expensive to construct than other types.
   d. they are better suited for high-pressure applications than other types.
   e. None of the above are true.
7. The most common cause of cylinder failure is ...
   a. improper cylinder mounting.
   b. contamination of the working fluid.
   c. misapplication of the cylinder.
   d. misalignment of the cylinder.
   e. over-temperature operation.
8. Which of the following cylinder types can apply a force to two separate loads at the same time?
   a. Tandem
   b. Duplex
   c. Double rod
   d. Both a and b
   e. Both b and c
   f. All of the above
9. A double-acting hydraulic cylinder has a diameter of 2 inches and a stroke of 12 inches. The rod diameter is 1 inch. The extension time of the cylinder is 3 seconds. What is the fluid flow rate?
   a. 0.054 gpm
   b. 3.26 gpm
   c. 7.34 gpm
   d. 2.45 gpm
   e. 13 gpm
10. A double-acting hydraulic cylinder has a cylinder area of 8 in^2 and a rod cross section of 4 in^2. The stroke of the cylinder is 6 inches. The retraction time is 4 seconds. What is the extension time?
   a. 8 seconds
   b. 2 seconds
   c. 4 seconds

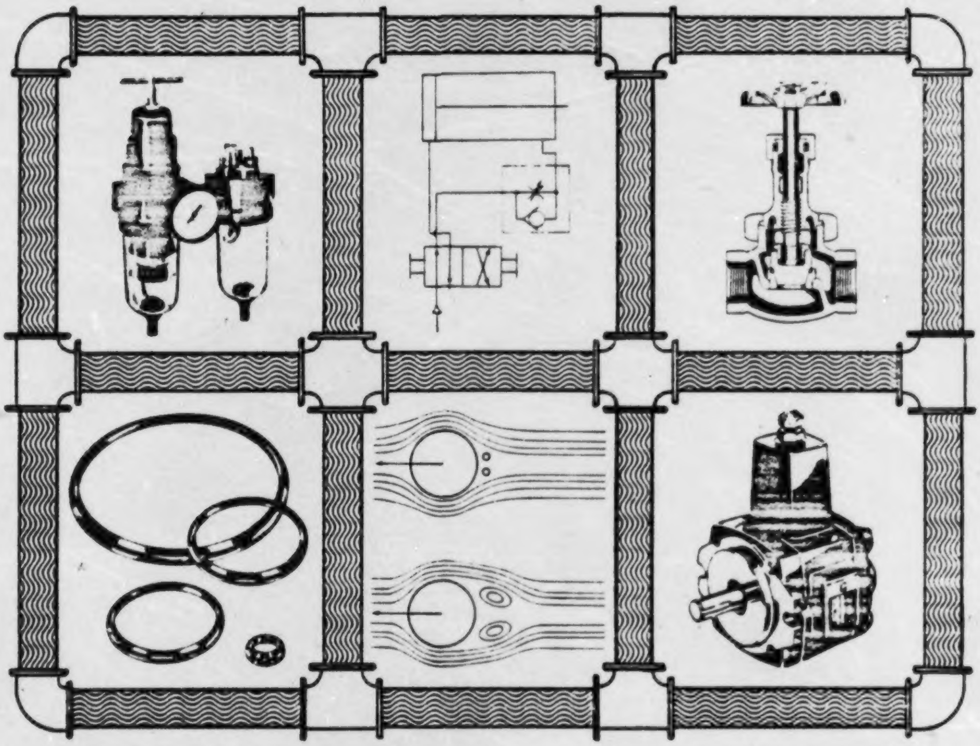
d. 5.66 seconds

e. Cannot be determined from the data given

ENERGY TECHNOLOGY

CONSERVATION AND USE

FLUID POWER



MODULE FL-06

FLUID DISTRIBUTION AND CONTROL DEVICES

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

The fluid distribution system of any fluid power system must deliver fluid power to the point of application at the proper time with the proper flow rate and pressure for the application. Such systems always include fluid conductor and control devices and may also contain means of storing fluidal energy and increasing the delivery pressure at the component.

This module discusses the major components of fluid distribution systems. Accumulators for storing hydraulic fluid under pressure and pressure intensifiers for increasing the pressure are described, as well as types and applications of fluid conductors and the connectors used with each. The discussion includes descriptions of function and application of directional control valves, pressure control valves, and flow control valves in hydraulic systems.

In the laboratory, the student will construct and operate fluid distribution systems using accumulators, pressure intensifiers, directional control valves, and sequence valves.

PREREQUISITES

The student should have completed Module FL-04, "Actuators and Fluid Motors."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Draw and label diagrams of the following accumulators and describe the functions and characteristics of each:
    a. Weight-loaded
    b. Spring-loaded
    c. Gas-loaded, nonseparable
    d. Gas-loaded piston
    e. Diaphragm
    f. Bladder

2. List three applications of accumulators and the type used for each application.
3. Explain the operation of a pressure intensifier.
4. Given the flow rate of a hydraulic conductor and the maximum allowed fluid velocity, calculate the diameter of conductor necessary.
5. Describe the materials used for each of the following types of fluid conductors, its application, and the connectors used with each:
    a. Rigid
    b. Semirigid
    c. Flexible
6. Describe the construction and operation of a four-way, three-position directional control spool valve.
7. List and explain three methods of activating a spool valve.
8. Explain the operation of a servo valve.
9. Explain the operation and application of each of the following types of pressure control valves:
    a. Pressure relief valve
    b. Unloading valve
    c. Sequence valve
    d. Pressure reducing valve
10. Explain the difference in the operation of a pressure-compensated flow control valve and a noncompensated flow control valve.
11. Explain how accumulators and unloading valves can be used to increase the energy efficiency of a hydraulic power system.
12. Construct and operate a circuit using an accumulator to power a pressure intensifier and a circuit for sequencing the operation of hydraulic cylinders.

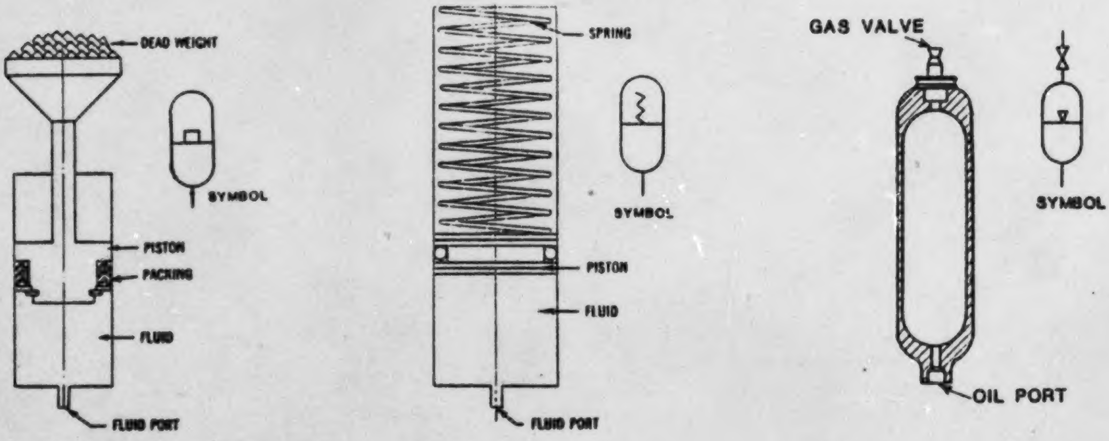
ACCUMULATORS

An accumulator is a device that stores the potential energy of an incompressible fluid under pressure by doing work against a dynamic force. This energy can be recovered for later use in the fluid power circuit.

ACCUMULATOR TYPES

There are three basic types of accumulators, each classified according to the means of applying force to the liquid in the accumulator. This may be accomplished with a weight-loaded piston, a spring-loaded piston, or by several methods of applying gas pressure above the liquid surface.

Figure 1a shows a weight-loaded accumulator and its fluid power symbol. Fluid pumped into the cylinder raises a large weight attached to the piston. The weight forces the liquid out of the cylinder at a later time, providing power. Weight-loaded accumulators are the only type that deliver a constant fluid pressure. They are large and heavy and must be mounted in a vertical position.



a. Weight-Loaded b. Spring-Loaded c. Nonseparator Type

Figure 1. Types of Accumulators.

The spring-loaded accumulator in Figure 1b uses the compression force of a spring to apply a force to the piston. Most spring-loaded accumulators are designed to deliver small fluid flow at relatively low pressures. Large or high-pressure models require a heavy spring and are heavy and bulky. These accumulators are not suited for applications requiring high cycle rates, as this results in spring fatigue and failure. The pressure delivered by spring-loaded accumulators is not constant but decreases as the spring extends.

Gas-loaded accumulators of several types operate according to the principle of Boyle's law, which states that the pressure of a gas varies inversely with volume at a constant temperature. The simplest type of gas-loaded accumulator is the nonseparator type shown in Figure 1c. It consists of a pressure tank with oil in the bottom and high-pressure gas in the top. Pumping more oil into the tank compresses the gas and raises the pressure. There is no physical barrier between the gas and oil, and this accumulator must be mounted vertically to maintain the separation. The major advantage of this accumulator is that is can store large amounts of oil in a relatively small space. However, gas is absorbed into the oil at the air-oil surface, which makes the fluid more compressible and results in spongy operation of actuators. The absorbed gas can also result in cavitation in high-speed pumps. For these reasons, nonseparator accumulators are unsuited for most systems. The symbol shown in this figure is used for all gas-loaded accumulators.

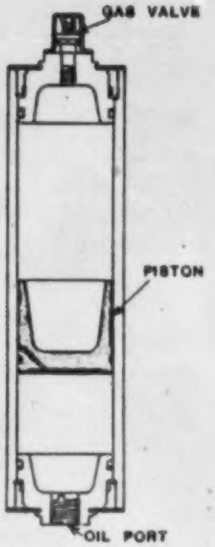


Figure 2.
Piston-Type
Accumulator.

Three types of separator gas-loaded accumulators maintain a seal between the oil and gas. Figure 2 shows a piston-type accumulator. Piston accumulators are expensive and are limited to small sizes. The friction of the piston seal may cause problems in low-pressure systems. Leakage around the seal tends to occur over a long period of time. These accumulators are used primarily with high or low temperature fluids or with fluids whose characteristics are not compatible with other gas-loaded accumulators. Piston seals can be provided for any fluid.

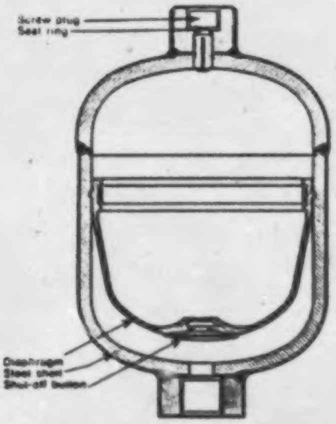


Figure 3. Diaphragm-Type
Accumulator.

Figure 3 shows a diaphragm-type separator accumulator. A flexible diaphragm is clamped between two shell halves. A shut-off button on the bottom of the diaphragm closes the inlet port and prevents extrusion of the diaphragm. The diaphragm can move from the bottom of the tank almost to the top, giving this accumulator the highest volume-to-weight ratio of any separator type. This type is used extensively in aviation applications.

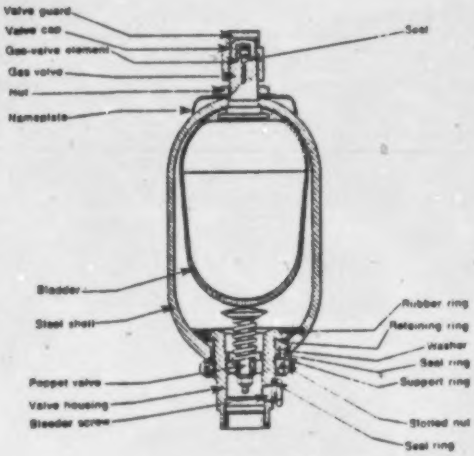

Valve guard
Valve cap
Gas-valve element
Gas valve
Nut
Nameplate
Seal
Bladder
Steel shell
Poppet valve
Valve housing
Bleeder screw
Rubber ring
Retaining ring
Washer
Seal ring
Support ring
Slotted nut
Seal ring

Figure 4. Bladder-Type Accumulator.

Figure 4 shows a bladder-type accumulator in which the gas is contained in a flexible synthetic rubber bladder. Its operation is similar to that of the diaphragm type. The bladder type must be mounted vertically to prevent oil from being trapped by the bladder as it expands. The quick response of the lightweight bladder provides the best performance for pressure regulation and pulsation dampening.

ACCUMULATOR APPLICATIONS

Accumulators are used as power-saving devices in several ways. In a system performing intermittent operations, a small pump can be used to continuously pump oil into an accumulator. Oil flow from the accumulator operates the actuators and provides an oil flow rate several times that delivered by the pump. This allows the use of a small pump and improves overall system efficiency by providing for more nearly constant pump output. Accumulators can be employed in a similar manner in any system to increase fluid delivery rate momentarily and, thus, increase the speed of an actuator. This is often done in rapid retraction of double-acting cylinders.

An accumulator can also be used to save power when a system requires high pressure but a small flow rate. The accumulator provides the pressure while the pump is unloaded by an unloading valve (described later in this module). This allows the pump to operate with the outlet pressure near atmospheric and requires little input power to the pump drive.

Another application of accumulators is to provide fluid pressure and power when the pump is turned off. Many industrial applications require positive positioning of actuators for long periods of time. Because of small leakage through components and valves, pressure must be maintained and a small oil flow must be provided. An accumulator can achieve this with the pump off.

A similar application is the use of an accumulator as a back-up power source for safety purposes. Pressure loss due to pump or component failure can cause hazards to equipment and personnel. An accumulator in the circuit can provide emergency fluidal power until the actuators can be properly positioned for safe shutdown.

One of the most important industrial applications of accumulators is the reduction or elimination of fluid pulsations. Some pulsation is present in all pump outlets, and it is a more serious problem with the more common gear pumps. These pulsations can cause a pulsating motion of actuators and can set up damaging vibrations in piping. The rapid closing of a valve can produce a high-pressure shock wave as the flowing oil is rapidly decelerated. The severity of the hydraulic shock (sometimes called water hammer) is greater at higher fluid velocities and can rupture fluid conductors or damage components. A properly chosen accumulator absorbs these shocks, thereby protecting the system. Bladder and diaphragm accumulators are used for this purpose because of their quick responses. Weight-loaded and spring-loaded accumulators and piston type gas-loaded models are not suitable for reducing pulsation shock.

ACCUMULATOR MAINTENANCE

The proper operation of any accumulator depends on the maintenance of the seals in good condition and the application of the proper force to the enclosed oil. In weight-loaded accumulators, force is provided by the weight and is present as long as the weight rests on the piston. The reduction of applied force in spring-loaded types occurs only if the spring is weakened or broken. Gas-loaded accumulators depend on the proper gas pressure. This pressure is usually specified and set with all the oil exhausted from the accumulator. Gas-loaded accumulators should be checked periodically and the proper pressure should be maintained.

The rupture of a diaphragm or bladder will eventually result in gas entering the hydraulic lines. This will cause sluggish motion of actuators and a reduction of accumulator pressure as more of the gas charge is lost. Leaks may not be evident unless the oil level of the accumulator drops to its minimum. Leaks can be detected by allowing all oil to flow from the accumulator and monitoring the gas pressure. If the gas pressure continues to drop after the accumulator is empty of oil, the gas seal is leaking.

PRESSURE INTENSIFIERS

Many hydraulic and pneumatic systems require one pressure for the operation of most of the system and a higher pressure for specific actuators. Pressure intensifiers are used to produce the higher pressures needed without a high-pressure pump. Module FL-04, "Pumps and Compressors," described a reciprocating pressure intensifier that provides a continuous flow of high-pressure oil. The type described here produces a momentary flow only.

Figure 5 is a single-acting hydraulic pressure intensifier. A piston with a large area is driven by low-pressure oil. Its piston rod, called a ram, is forced into a smaller diameter cylinder. Since the forces on each end of the piston rod are the same, the ratio of pressures is the ratio of areas. In this model, the piston is retracted by spring force. Other intensifiers may use gravity or the pressure caused by the load itself for retraction. Double-acting pressure intensifiers retract the piston by the application of high-pressure fluid above the piston. The high-pressure fluid is always oil, but either oil or compressed air may be used for the low-pressure fluid. With the proper valving pressure, intensifiers can be used as reciprocating pumps that provide intermittent flow.

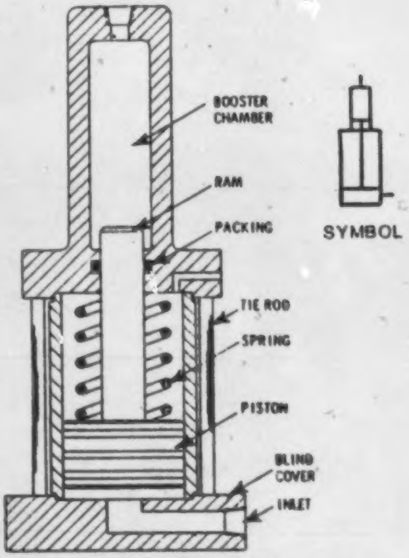


Figure 5. Typical Single-Acting Hydraulic Booster.

FLUID CONDUCTORS AND CONNECTORS

In fluid power systems, power is transmitted by fluid flow through conductors and fittings. In hydraulic systems, the conductor system takes oil from the reservoir to the pump, then to the actuators, and finally back to the reservoir. The conductors used must be capable of withstanding the applied pressure and must be large enough to allow fluid flow at velocities low enough to prevent turbulence. Pump inlet lines are sized to give fluid velocities of not more than 4 ft/sec. Higher velocities result in lower inlet pressures, which may cause pump cavitation. The maximum recommended velocity for high-pressure lines is 20 ft/sec. Higher velocities result in turbulent flow, which wastes power and heats the oil. The velocity values given are for any average velocity — not for the maximum velocity at the center of the pipe. Example A illustrates the sizing of conductors.

EXAMPLE A: SIZING HYDRAULIC CONDUCTORS.

Given: A pump delivers oil at a rate of 50 gpm. The maximum fluid velocity in the outlet pipe must be limited to 20 ft/sec for efficient operation.

Find: The minimum acceptable inner diameter of the pipe.

Solution: Flow Rate:

$$Q = (50\ \text{gal/min})\left(\frac{1\ \text{min}}{60\ \text{sec}}\right)\left(\frac{231\ \text{in}^3}{\text{gal}}\right)$$

$$Q = 192.5\ \text{in}^3/\text{sec}$$

Fluid Velocity:

$$v = (20\ \text{ft/sec})\left(\frac{12\ \text{in}}{1\ \text{ft}}\right)$$

$$v = 240\ \text{in/sec}$$

$$\text{Fluid Velocity} = \frac{\text{Flow Rate}}{\text{Conductor Area}}$$

$$v = \frac{Q}{A}$$

$$A = \frac{Q}{v}$$

$$= \frac{192.5\ \text{in}^3/\text{sec}}{240\ \text{in/sec}}$$

$$A = 0.802\ \text{in}^2$$

$$A = \frac{\pi d^2}{4}$$

Example A. Continued.

$$d = \sqrt{\frac{4A}{\pi}}$$

$$= \sqrt{\frac{(4)(0.802\ \text{in}^2)}{3.14}}$$

$$= \sqrt{1.02\ \text{in}^2}$$

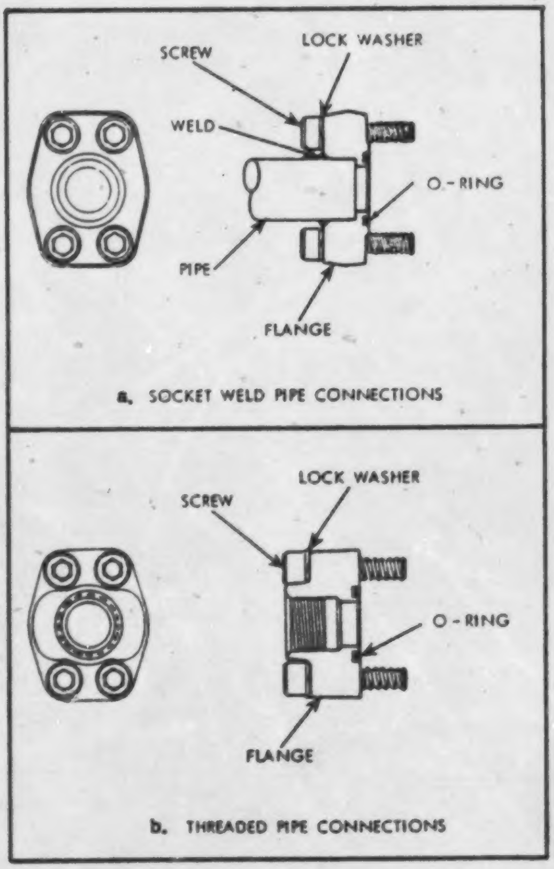
$$d = 1.01\ \text{in}$$

The inner diameter of the conductor must be greater than 1.01 in.

RIGID PIPES

Rigid pipes are fluid conductors that cannot be bent around obstacles. They are straight pieces of conductor that have male threads and are connected with pipe fittings. Steel is the only material that is widely used for pipes in hydraulic power systems. Steel pipe is available in many standard sizes and strengths and may be manufactured to contain any practical fluid pressure. . Pipe size is specified according to the size of the threads. Both inner and outer diameters of standard pipes vary as the wall thickness varies.

Figure 6 shows flanged connectors used to connect rigid pipe to fluid power components. These connectors bolt to the component and seal by means of an O-ring. Pipe can be welded to the connector or screwed into female threads in the connector. Hydraulic pipe has tapered, dry-seal threads. The pipe and connector threads make a compression seal at the crests and roots of the threads.



a. SOCKET WELD PIPE CONNECTIONS

b. THREADED PIPE CONNECTIONS

Figure 6. Flanged Connections for Large Pipes (Straight-Type).

Each time a joint is reassembled, the threads must be tightened further to provide a positive seal. Frequently, this means that some of the pipe in a rigid system must be replaced with slightly longer pieces when the system is disassembled. This problem can be overcome to a large degree by using Teflon tape on the threads.

Steel pipe provides the highest pressure service, but, because of the difficulty of its installation, it is usually limited to those applications. Rigid pipe is sometimes used for internal connections in a machine driven by fluid power where mechanical or hydraulic shock make a strong or rigid conductor desirable. Compressed air conductors are usually made of galvanized pipe to resist rust formation. Galvanized pipes should never be used for hydraulic oils, as the zinc coating rapidly increases the oxidation rate of many oils.

SEMIRIGID TUBING.

Semirigid tubing is a metal fluid conductor that is not flexible in operation but may be bent during installation. It is the most popular type of hydraulic conductor because it is easily installed and requires less space and fewer connectors than pipe. The use of tubing in pneumatic systems is usually limited to short runs near the point of application of the air. Seamless steel is the most common type of tubing, but stainless steel, aluminum, and copper tubing are sometimes used. Copper tubing is not recommended for hydraulic oils because the copper acts as a catalyst in breaking down oil additives and because it can work harden from vibrations and become brittle.

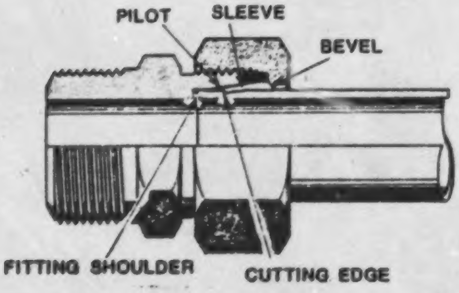


Figure 7. Flareless Tube Fitting.

Tubing is available in several wall thicknesses. Its size is specified by the outer diameter of the tubing. The pressure handling of tubing varies with diameter and wall thickness. Some steel tubing can operate at pressures above 5000 psi.

Tubing cannot be threaded but is connected with a variety of tubing connectors. Figure 7 shows a popular type of flareless connector used with tubing that cannot be flared. A cutting edge on the inner surface of the sleeve cuts into the surface of the tubing and prevents it from being forced out of the connector. The sleeve is compressed along its length to grip and reinforce the tubing at the connector. This forms a positive seal without constricting the tubing.

Figure 8 is a Swagelok tubing connector. It grips the tubing by means of two metal ferrules that are compressed onto the tubing. The compression forms a tight seal but does not noticeably constrict the inner diameter. This type of connector can be disassembled and reassembled many times without leakage. It will also withstand greater pressure than the tubing itself. This type of connector has become very popular because of its reliability and ease of installation.

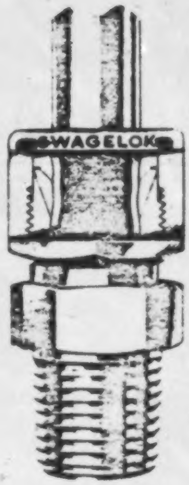


Figure 8. Swagelok Tube Fitting.

Figure 9 shows several other common types of tubing connectors. The 37° flare fitting is the most widely used fitting for tubing that can be flared. The 45° flare fittings were used for high-pressure applications before compression fittings were developed, and they are still in use today. O-ring fittings are also used for high-pressure seals of tubing that cannot be flared.

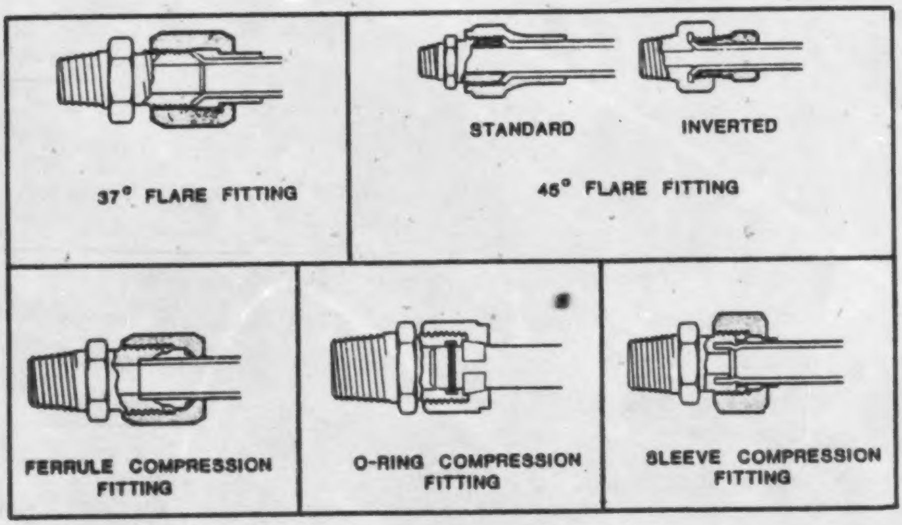

37° FLARE FITTING
STANDARD
INVERTED
45° FLARE FITTING
FERRULE COMPRESSION FITTING
O-RING COMPRESSION FITTING
SLEEVE COMPRESSION FITTING

Figure 9. Threaded Fittings and Connectors Used with Tubing.

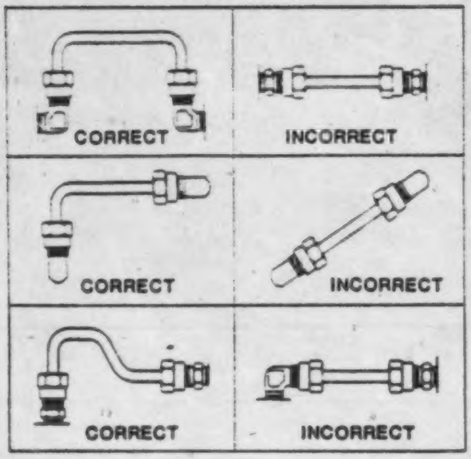


Figure 10. Tubing Installation in a Fluid System.

Several precautions are necessary in the installation of tubing. Care must be taken to avoid mechanical stress. Longer lengths of tubing should be supported, and tubing should never be used to support any component. All parts installed in tubing lines, such as heavy fittings and valves, should be bolted down to prevent motion that could lead to tubing fatigue. Straight line connections, particularly for short lengths, should be avoided. Tubing tends to lengthen and contract slightly as pressure is applied and released. This produces stress on straight tubing sections, which can lead to failure. Tubing connections should always contain a bend to allow some flexure. Figure 10 shows correct and incorrect ways to make tubing connections.

FLEXIBLE HOSES

Flexible hoses are used to connect fluid power components whenever the component is subjected to movement. These hoses are made of layers of wire braid and synthetic rubber with an inner conductor that is compatible with the fluid used. Several styles are available with maximum working pressures from 250 to 5000 psi. Higher pressure types have several layers of wire braid that may or may not be alternated with layers of rubber.

Hoses are available with male and female pipe fittings and with compression fittings. Fittings may be straight or may have angles of 45° or 90°. Permanent fittings are attached to the hose ends during manufacturing and cannot be removed and reused. Reusable fittings are compression fittings designed to grip the hose between a sleeve inside the hose and a compression ring on the outside. This type of fitting can be removed from one piece of hose and installed on another.

Systems in which components are frequently disconnected may employ quick disconnect couplings (Figure 11). These are available in straight through models that do not seal either the male or female connector when disconnected and in models that automatically seal one or both conductors. The connector shown in Figure 11 is a two-way shut-off coupling. The plungers are held against seals by fluid pressure when the couplers are disconnected. During operation, the couplers are held together by ball bearings that catch in a groove in the male connector and are held in place by the locking sleeve of the female connector. When the locking sleeve is removed, the ball bearings may retract, and fluid pressure forces the couplers apart and seals the ends. These connectors should be protected from dust and dirt, as these particles could easily enter and contaminate the fluid lines.

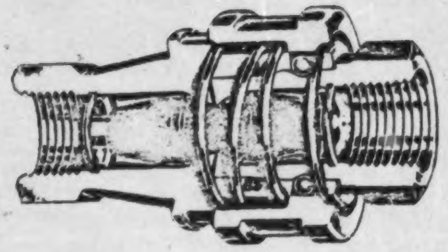


Figure 11. Cross-Sectional View of Quick Disconnect Coupling.

Under pressure, a hose may change in length, becoming either slightly longer or shorter depending on the type of hose. Connecting hoses should always contain some slack to avoid tension. Hoses should never be twisted in installations, as pressurizing the hose tends to straighten it and may loosen the connector. All hose bends should be made with a radius large enough to prevent pinching of the hose, and the motion of components should not restrict or kink the hose. Figure 12 shows several correct and incorrect hose installations.

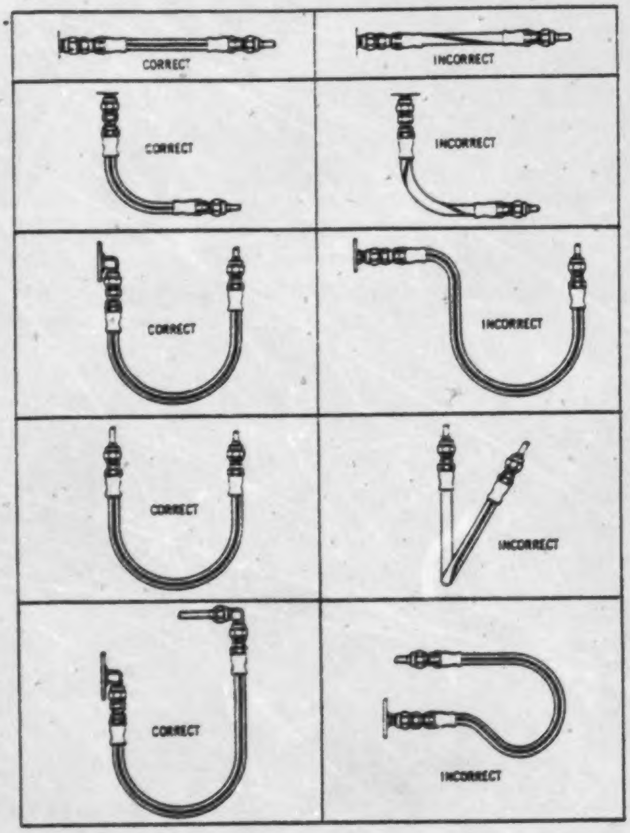


Figure 12. Hose Installations.

PLASTIC TUBING

Plastic tubing has gained in popularity for low-pressure fluid power applications because it is inexpensive and easy to install. It is widely used in pneumatic systems because the pressure is usually under 100 psi. Low-pressure hydraulic systems may also use plastic tubing. Fittings used with plastic tubing are almost identical to those used with steel tubing.

FLUID CONTROL DEVICES

Fluid control devices consist mainly of valves for controlling the direction of fluid flow, fluid pressure, or fluid flow rate. A wide variety of control components is available. Some of the more common ones are discussed here.

DIRECTIONAL CONTROL VALVES

Directional control valves (DCV) are used to control the direction of fluid flow in fluid power systems. Figure 13 illustrates a check valve, the simplest type of directional control valve. The check valve allows flow in one direction only. This particular model is a simple spring-loaded poppet valve in the fluid flow line. Fluid flow from one direction pushes the poppet open, allowing flow. Pressure applied from the back side of the valve acts with spring tension to close the valve, preventing reverse flow. Check valves are used in both hydraulic and pneumatic systems. Some are pilot operated and can be controlled by fluid pressure from a remote location.

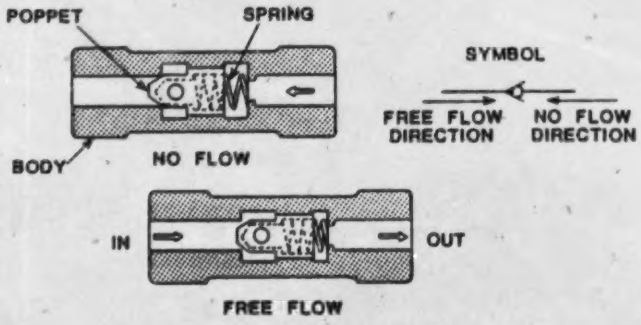


Figure 13. Operation of Check Valve.

Other types of directional control valves are used to direct fluid flow to and from components. Two-way valves have two ports and can be opened or closed to control flow in a single conductor. Several valve types may be used for this application. Three-way valves have three ports: one connected to the fluid power source, one to the power component, and the third to the reservoir in a hydraulic system or exhaust in a pneumatic system. These valves are used to connect a single-acting cylinder to the pump for extension or to the drain for retraction. Some have a third position in which fluid flow through the valve is blocked, locking the position of the actuator.

Four-way control valves have four ports and are used to control double-acting cylinders, fluid motors, and other reversible fluid actuators. The four ports are connected to the pump, reservoir, and each port of the actuator. The most common type of four-way control valve is the spool valve shown schematically in Figure 14. It consists of a valve body containing fluid ports and passages and a spool that can be moved from side to side. The center port on the bottom of the diagram is connected to the fluid power source. The two outer ports of the diagram are actually connected internally within the valve and to a fluid conductor leading to the reservoir of a hydraulic system or to exhaust in a pneumatic system. The upper ports lead to the ends of a double-acting cylinder or other actuator. The schematic diagram of this valve shows the two connections possible with a two-position valve. One position extends the cylinder and the other retracts it.

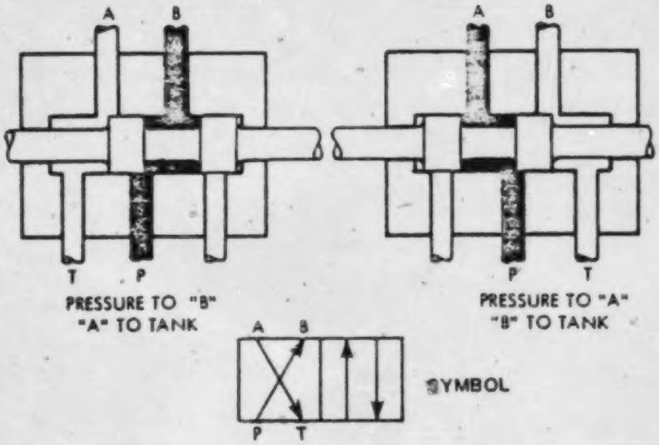


Figure 14. Spool Positions Inside Four-Way Valve.

The seals in spool valves are nonpositive seals and allow a small amount of oil flow through the space between the spool and the valve body. This fluid is drained back to the tank through the tank connection. Spool valve failure usually occurs because of worn seals, which results in excessive fluid leakage.

Figure 15 shows a manually actuated, spring-centered, three-position, four-way control valve. In the center position, all ports of this valve are

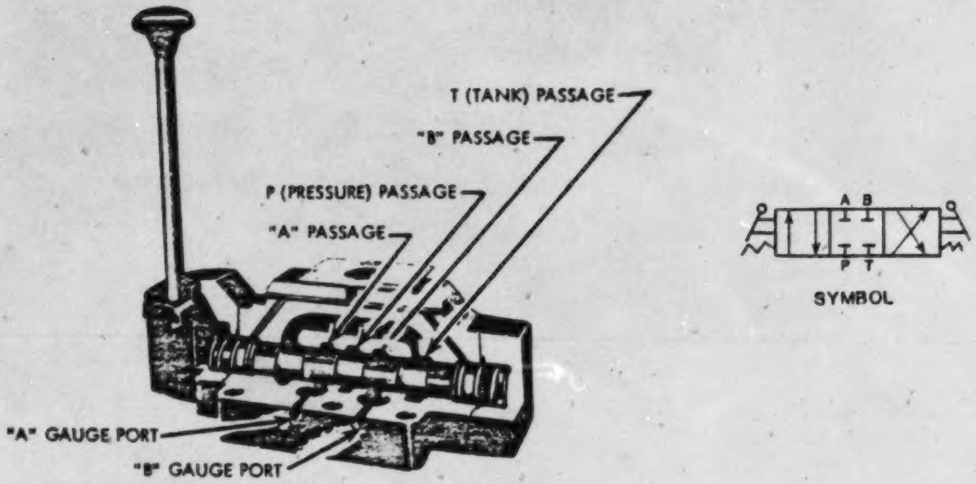


Figure 15. Manually Actuated, Spring-Centered Three-Position, Four-Way Valve.

blocked and no flow occurs. Springs on the ends of the spool return this valve to the center position automatically. All four-way control valves have the same connections for the two end positions.

Spool valves may also be actuated by fluidal or electrical input signals. In a pilot-operated valve, a fluid cylinder is located at each end of the spool with its piston connected to the spool. Applying pressure to one of these cylinders shifts the valve spool in the direction away from that end of the valve body. The use of pilot-operated control valves will be discussed in Module FL-07, "Fluid Circuits." A solenoid-actuated valve is one in which the valve spool is moved by an electrical solenoid. It allows direct electrical control of the direction of fluid flow. Pilot-operated and solenoid-actuated control valves usually have springs for centering the spool when the input signal is removed.

Most directional control valves are of the spool type, but others are also in use. Figure 16 shows a rotary DCV consisting of a rotor with oil passages closely fitted inside a body with oil ports. Rotating the control handle moves the rotor to one of the three positions indicated. The symbol for this type of valve is the same as that of a spool valve. The symbol indicates the function of the valve — not physical construction.

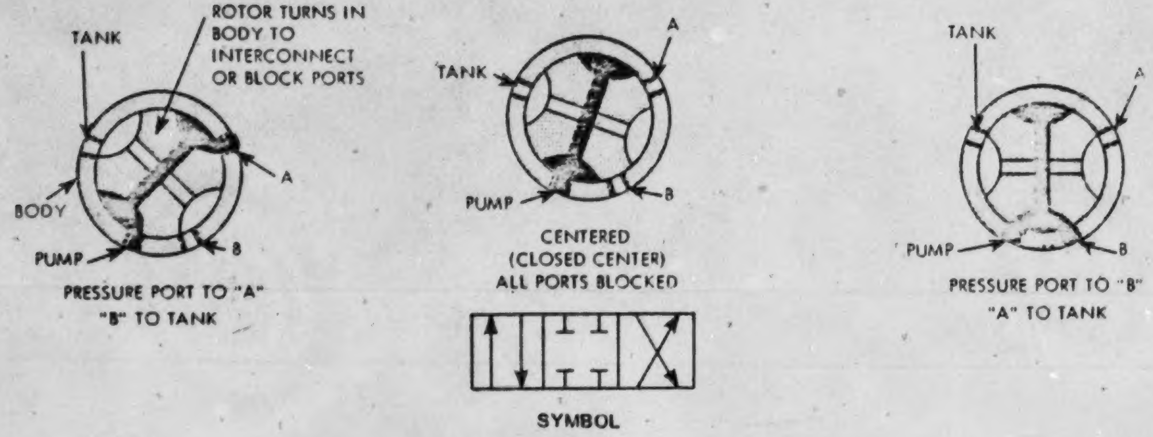

ROTOR TURNS IN BODY TO INTERCONNECT OR BLOCK PORTS
TANK
A
BODY
PUMP
B
PRESSURE PORT TO "A"
"B" TO TANK
TANK
A
PUMP
B
CENTERED
(CLOSED CENTER)
ALL PORTS BLOCKED
SYMBOL
TANK
A
PUMP
B
PRESSURE PORT TO "B"
"A" TO TANK

Figure 16. Rotary Four-Way Valve.

Figure 17 shows a shear-flow rotary direction control valve. The fluid passages of this valve have the same pattern as the valve in Figure 16, but the special seal design allows this valve to act as both a directional control valve and a flow control valve.

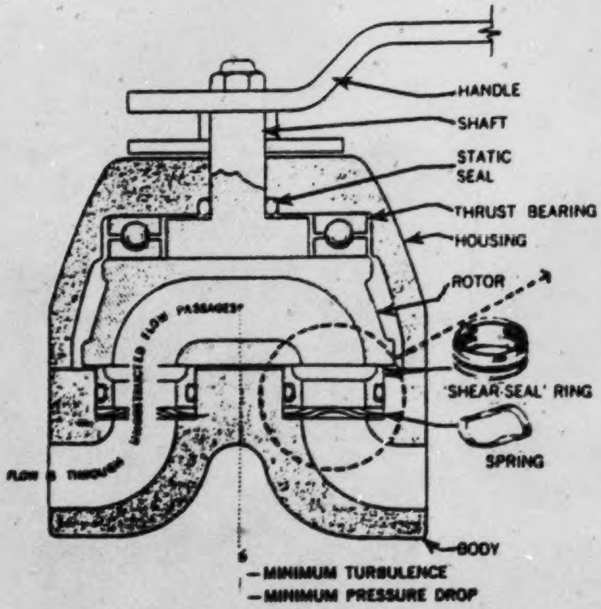

HANDLE
SHAFT
STATIC SEAL
THRUST BEARING
HOUSING
ROTOR
UNRESTRICTED FLOW PASSAGES
'SHEAR-SEAL' RING
SPRING
FLOW IS THROUGH
BODY
—MINIMUM TURBULENCE
—MINIMUM PRESSURE DROP

Figure 17. Shear-Flow Rotary Directional Control Valve.

Rotary directional control valves are usually activated manually or mechanically. Both spool and rotary DCVs are used in pneumatic as well as hydraulic systems.

SERVO VALVES

Servo valves are directional control spool valves that can control both the direction of flow and the flow rate. They are similar to the rotary valve in Figure 17. Servo valves are used with feedback sensing devices to provide very accurate position, velocity, or acceleration of an actuator. Figure 18 shows the principle with a mechanical feedback link used to position a piston in a cylinder. The position of the valve spool is controlled manually; the position of the valve body is controlled by the mechanical linkage to the piston. If the spool in the figure is moved to the right, oil will flow from the inlet port to port A and from port B to the tank. This causes the piston and the valve body to move to the right. The speed of the motion decreases as the center portion of the spool comes into alignment with the inlet port. When the inlet port is completely blocked, the piston is held in place. This type of control is used in power steering in automobiles. The feedback to the servo valve may also be electrical or fluidal.

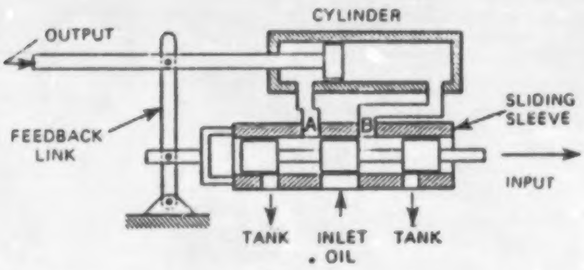


Figure 18. Mechanical-Hydraulic Servo Valve.

PRESSURE CONTROL VALVES

In pneumatic systems, the pressure is controlled by pressure regulators (described in Module FL-03, "Fluid Storage, Conditioning and Maintenance"). In hydraulic systems, pressure control is achieved by a variety of pressure control valves.

The most widely used pressure control valve is the pressure relief valve shown in Figure 19. The inlet from the pump is sealed by a spring-loaded piston (1). When pressure is less than the valve setting, the valve remains closed (2). The valve is closed until it reaches the cracking pressure. At this pressure, the valve begins to open, and oil flows through the valve and back to the hydraulic reservoir (3). Higher pressures cause the valve to open wider until it will carry the entire pump output if the rest of the system is closed. Almost every hydraulic pump is protected by a pressure relief valve.

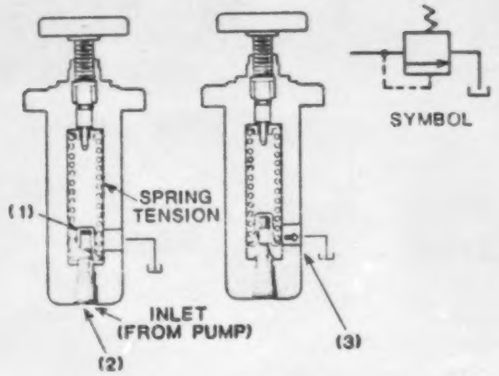


Figure 19. Simple Pressure Relive Valve.

The schematic diagram of the pressure relief valve indicates that it is a pilot-operated deivce. This is a device in which fluid pressure moves a piston. In the valve in Figure 19, the pilot pressure is the pressure of the pump outlet applied directly to the valve piston. Other types of pressure relief valves can be operated by pilot signals from other locations.

An unloading valve is similar to a pressure relief valve but is constructed to operate due to pressure applied to a pilot port. This valve remains closed until pressure at the port reaches a preset level. Then the valve opens and remains open as long as the pressure is applied to the pilot port. Unloading valves are used to "unload" the pump in hydraulic circuits using accumulators for energy storage. The pilot pressure is applied by the pressure of the accumulator. The unloading valve is used to allow the entire pump output to drain into the tank at atmospheric pressure. This means that the pump does not pump liquid against pressure and consumes very little energy. A pressure relief valve requires that the pump be fully loaded when no oil is required by the system. The maximum pressure must be maintained to operate the pressure relief valve. This causes unnecessary consumption of pump drive power and converts this power to heating of the oil in the pressure relief valve. Unloading valves and accumulators improve the energy efficiency and thermal properties of hydraulic systems. Its schematic symbol is the same as that of a pressure relief valve, but its pilot is connected to some other component.

A sequence valve operates exactly like a pressure relief valve, and is used to control the sequence of operation of hydraulic actuators. A sequence valve is used to control the operating sequence of two single-acting cylinders. The valve is set to remain closed at the pressure required for the operation of one cylinder. When pressure is applied to the circuit, the valve remains closed and the cylinder extends. When it reaches the end of its travel, the pressure rises and the sequence valve opens to operate the other cylinder.

Another type of pressure control valve is the pressure reducing valve. This valve does not block fluid flow but maintains a reduced pressure downstream from the valve for the operation of lower pressure components. The pressure reducing valve allows a portion of the oil entering it to flow back to the tank from the spring chamber. Only enough oil is allowed to flow out the valve outlet to maintain the reduced pressure.

FLOW CONTROL VALVES

Flow control valves control the rate of fluid flow through the valve. In most pneumatic systems, simple needle valves are used for flow control. Flow control valves for hydraulic systems usually incorporate a check valve to prevent reverse flow. In the noncompensated flow control valve, the flow rate varies with pressure. This type of valve is suitable only for systems in which the pressure is relatively constant during valve operation. The pressure-compensated flow control valve adjusts to changes in system pressure in order to maintain an almost constant flow at all pressures.

OTHER CONTROL DEVICES

Several other control and safety devices are used in fluid power systems. Figure 20 shows a hydraulic fuse for pump protection. It is a thin metal disc that ruptures if the pressure exceeds a certain value. The schematic diagram shows a hydraulic fuse used as fail-safe protection for a pressure-compensated pump. If the pump pressure control fails, the hydraulic fuse protects the pump components.

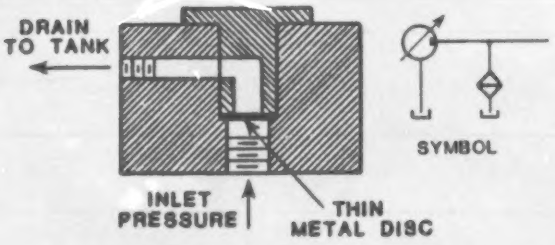


Figure 20. Hydraulic Fuse.

Hydraulic systems often include temperature-activated electric switches that shut down the system or sound an alarm if the oil temperature exceeds a certain value. In pneumatic systems, pressure-activated switches are used to turn the compressor on and off.

SUMMARY

The fluid distribution system of a fluid power system includes fluid conductors and valves and may contain accumulators and pressure intensifiers. Fluid conductors in pneumatic systems are usually galvanized pipe with short runs of hose or metal or plastic tubing for component connections. The most widely used hydraulic fluid conductor is steel tubing, but steel pipe and flexible hose are also important in hydraulic systems.

Fluid control valves can be grouped into three basic classes. Directional control valves control the direction of fluid flow to and from components. The most common type is the spool valve. Pressure control valves allow fluid flow only under certain pressure conditions. These include pressure relief valves, unloading valves, sequence valves, and pressure reducing valves. Fluid flow valves control the rate of fluid flow through the valve.

Hydraulic fluid distribution systems may also contain accumulators for storing energy in fluid under pressure. Both hydraulic and pneumatic systems may use pressure intensifiers to produce high pressures for the operation of some components.

EXERCISES

1. Explain the uses of accumulators in hydraulic circuits, including two ways they can make systems more energy efficient.
2. Draw a diagram of a double-acting pressure intensifier in a pneumatic circuit. Include the valves necessary for its operation.
3. A hydraulic pump delivers fluid at a flow rate of 150 gpm. Determine the minimum acceptable diameters for the pump suction line and the pump outlet line.

4. Explain the applications of each of the following types of fluid conductors and the reasons they are chosen for those applications:
   a. Rigid
   b. Semirigid
   c. Flexible
5. Draw schematic symbols for each of the following valve types and describe the function of each:
   a. Three-position, four-way DCV
   b. Two-position, three-way DCV
   c. Pressure relief valve
   d. Unloading valve
   e. Sequence valve
   f. Pressure reducing valve
   g. Noncompensated flow control valve
   h. Pressure-compensated flow control valve
6. Explain, with a diagram, the operation of a servo valve.
7. Explain the difference in energy efficiency of a system using a pressure relief valve and one using an unloading valve.

LABORATORY MATERIALS

Hydraulic power unit
Pressure relief valve
Two double-acting hydraulic cylinders
Single-acting hydraulic cylinder
Pressure intensifier
Accumulator (spring-loaded or gas-loaded)
DCV
Two check valves
Two sequence valves
Two pressure gauges
Connecting hydraulic hoses

LABORATORY PROCEDURES

1. Construct the hydraulic circuit shown in Figure 21. This circuit illustrates the operation of both accumulators and pressure intensifiers.
2. Fill the high-pressure section of the pressure intensifier and the hose to the cylinder with oil. The pistons of both should be fully retracted. The pressure intensifier must have sufficient volume displacement to fully extend the cylinder.
3. Turn on the hydraulic power unit. Operate the DCV to assure proper circuit operation.
4. Retract the cylinder, measure and record P_1 in the Data Table, and turn off the hydraulic power unit.

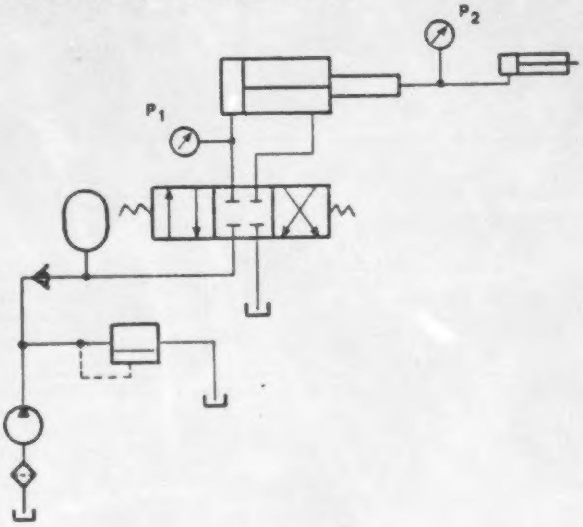


Figure 21. Accumulator-Pressure Intensifier Circuit.

5. Operate the circuit. Measure and record both pressures at the full extension of the piston. Operate the circuit a total of four cycles or until it will no longer operate. Record both pressures at the full extension of the piston on each stroke.
6. Explain the operation of each component in the system. Include the pressure ratio of the pressure intensifier and the reasons for any pressure variations between successive piston strokes.
7. Disassemble the circuit and assemble the cylinder sequence circuit shown in Figure 22.
8. Before operating this circuit, predict the sequence of actuator operation, starting with both pistons

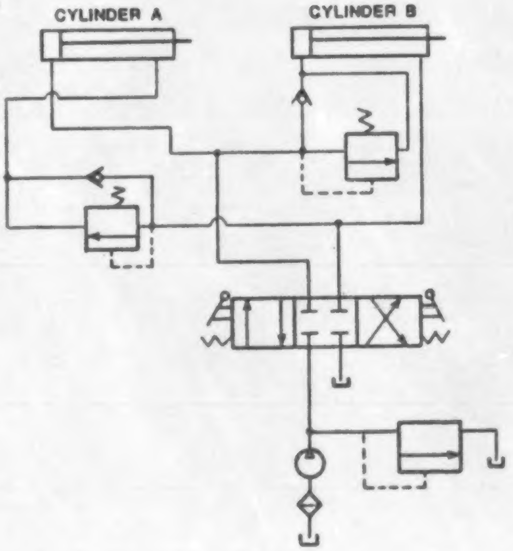


Figure 22. Cylinder Sequence Circuit.

fully retracted and continuing for a full cycle of the circuit. Record this in the Data Table.

9. Operate the circuit. Were your predictions correct?
10. Explain the operation of each component in the circuit.

DATA TABLE

DATA TABLE.

Accumulator-Pressure Intensifier Circuit

Trial	P_1 (psig)	P_2 (psig)
Initial		
1		
2		
3		
4		

Explanation:

Cylinder Sequence Circuit

Predicted sequence of operation:

Circuit explanation:

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Stewart, Harry L. and Storer, John M. Fluid Power. Indianapolis, IN: Howard W. Sams and Co., Inc., 1977.

GLOSSARY

Accumulator: A device for storing energy in a hydraulic system by storing hydraulic fluid under pressure.

Check valve: A valve that allows flow in one direction only.

Directional control valve: A fluid control valve that controls the direction of fluid flow to and from components.

Flexible hose: A fluid conductor that is flexible in use — usually a hose reinforced with wire braid.

Noncompensated flow control valve: A valve for controlling the flow of hydraulic fluid in which fluid flow rate varies with fluid pressure.

Pressure-compensated flow control valve: A valve for controlling the flow rate of hydraulic fluid in which the flow rate is the same for all pressures.

Pressure intensifier: A double cylinder and piston device used to produce higher pressures in pneumatic and hydraulic systems.

Pressure relief valve: A valve that opens when the pressure on its inlet exceeds a certain value — used for pump protection.

Pressure reducing valve: A valve that maintains a lower pressure downstream from the valve.

Rigid pipe: A fluid conductor that is connected with pipe fittings and cannot be bent — usually steel pipe.

Semirigid tubing: A fluid conductor that is not flexible in use but can be bent for installation — usually steel tubing.

Sequence valve: A pressure relief valve used to delay the operation of one actuator until another has completed its operation.

Servo valve: A directional control valve that has feedback control and can control fluid flow – used for accurate positioning.

Unloading valve: A pilot-controlled pressure relief valve that allows a pump to deliver fluid at atmospheric pressure while the system is powered by an accumulator.

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TEST

1. Which of the following accumulators can be used effectively for pulsation dampening?
   a. Spring-loaded type
   b. Gas-loaded piston type
   c. Gas-loaded bladder type
   d. Weight-loaded type
   e. Both b and c
2. Pressure intensifiers ...
   a. may be powered by either compressed air or hydraulic fluid.
   b. may use either compressed air or hydraulic fluid as the high-pressure fluid.
   c. can provide continuous flow at high pressure with the proper valving.
   d. Both a and b are true.
   e. Both a and c are true.
3. The maximum fluid velocity in a pipe carrying 80 gpm is 15 ft/sec. What is the minimum allowable diameter of the pipe?
   a. 5.3 inches
   b. 2.2 inches
   c. 1.7 inches
   d. 5.1 inches
   e. 4.3 inches
4. Semirigid hydraulic conductors ...
   a. are connected with pipe fittings.
   b. are not widely used because they are too flexible.
   c. cannot be used at pressures above 1000 psig.
   d. should never be used in straight lengths for short connections.
   e. are more difficult to install than rigid types.
5. Which of the following should never be used for hydraulic oil conductors?
   a. Copper tubing
   b. Galvanized pipe
   c. Plastic tubing
   d. Both a and b
   e. All of the above

6. A three-way directional control valve can be used to control which of the following components?
   a. Single-acting cylinder
   b. Double-acting cylinder
   c. Constant speed hydraulic motor
   d. Reversible hydraulic motor
   e. Both a and c
7. Which of the following is not true of spool-type four-way directional control valves?
   a. They always block fluid flow to and from the actuator while in the center position.
   b. They have nonpositive seals and allow some oil leakage at all times.
   c. They may be designed to return the pump output directly to the reservoir while in the center position.
   d. They are not as widely used as rotary DCVs.
   e. Both a and b are true.
   f. Both b and c are true.
8. Which of the following pressure control valves is used to increase the energy efficiency of a hydraulic system?
   a. Pressure relief valve
   b. Pressure reducing valve
   c. Sequence valve
   d. Unloading valve
   e. Pressure-compensated valve
9. Most pneumatic systems use which of the following for flow rate control?
   a. Pressure regulators
   b. Pressure-compensated flow valves
   c. Needle valves
   d. Pressure reducing valves
   e. Both a and c
10. Servo valves for position control include which of the following design features?
   a. They can control both direction of flow and rate of flow.
   b. They have a stationary spool and a manually positioned valve body.

c. They connect pump pressure to both sides of the actuator when the load is in the correct position.

d. They require electrical sensing circuits.

e. Both a and b are true.

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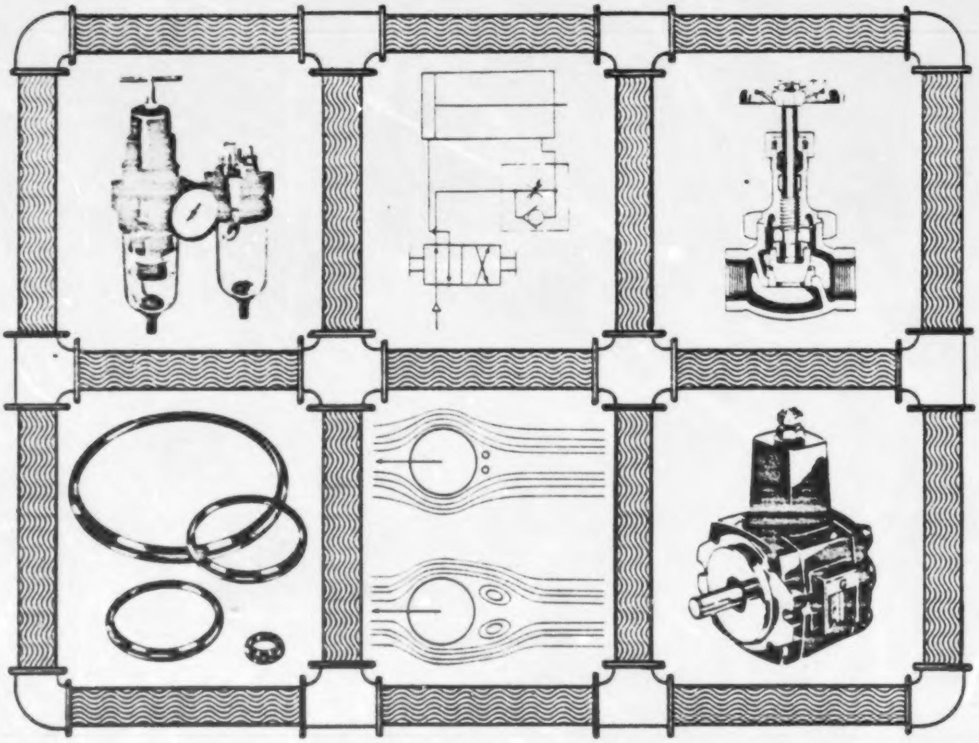
ENERGY TECHNOLOGY

CONSERVATION AND USE

FLUID POWER



MODULE FL-07

FLUID CIRCUITS

CORD

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

Fluid power circuits are always designed around the circuit actuators and should be as simple as possible to accomplish the desired results. In pneumatic circuits, the actuator speed depends on the rate at which the delivery system can provide compressed air at the actuator and the resistance to flow in the actuator exhaust. In hydraulic systems, actuator speed depends entirely on the flow rate of oil to the actuator.

This module discusses the basic design features of pneumatic and hydraulic circuits and controls. Topics include basic hydraulic and pneumatic circuits, speed control, motor control, synchronous operation of actuators, methods of increasing the speed of hydraulic actuators, and the overall efficiency of hydraulic systems.

In the laboratory, the student will construct two hydraulic circuits for operating the same component — one using a pressure relief valve and one using a pump unloading valve. The efficiency of the two circuits will be measured and compared.

PREREQUISITES

The student should have completed Module FL-06, "Fluid Distribution and Control Devices."

OBJECTIVES

Upon completion of this module, the student should be able to:

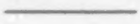
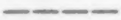
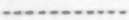
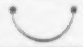
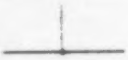
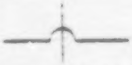
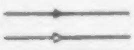
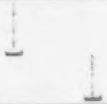
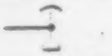
1. Explain the operation of a given fluid power circuit and identify each component.
2. Explain the basic procedure used in designing simple hydraulic circuits.
3. Explain the factors that limit the speed of operation of actuators in pneumatic and hydraulic circuits.
4. Explain three methods of flow control used in hydraulic circuits, and state which method is used in pneumatic circuits.

5. Draw, label, and explain circuits for accomplishing synchronous motion in the following:
   a. Hydraulic cylinders
      (1) by series connection
      (2) using motors as synchronizers
   b. Hydraulic motors
   c. Pneumatic cylinders
6. Explain how each of the following is used to increase actuator speed in a hydradulic circuit:
   a. Regenerative circuit
   b. Accumulators
7. Explain how the speed of a pneumatic cylinder can be increased.
8. Draw and label hydraulic circuits with the following features and explain how each saves in equipment cost and operating energy:
   a. Pump unloading with center position of DCV
   b. Pump unloading with an unloading valve
   c. Double-pump system
   d. Accumulator used as a leakage compensator
   e. Accumulator in a double pump circuit
9. Construct two hydraulic circuits for powering the same load — one using a pressure relief valve and the other using a pump unloading valve. Determine the energy consumption and efficiency of each circuit during a full cycle and compare the two.

FLUID POWER SYMBOLS

Several symbols used in fluid power schematic diagrams have been introduced and used in the previous modules in this course. Table 1 lists some of the more common graphical symbols that conform to the American National Standards Institute (ANSI) specifications. Many of these symbols will be used in the circuit diagrams in this module. Refer to this table as necessary for component identification.

TABLE 1. ANSI SYMBOLS OF HYDRAULIC COMPONENTS.

LINES AND LINE FUNCTIONS	
LINE, WORKING	
LINE, PILOT (L>20W)	
LINE, DRAIN (L<5W)	
CONNECTOR	
LINE, FLEXIBLE	
LINE, JOINING	
LINE, PASSING	
DIRECTION OF FLOW, HYDRAULIC PNEUMATIC	
LINE TO RESERVOIR ABOVE FLUID LEVEL BELOW FLUID LEVEL	
LINE TO VENTED MANIFOLD	
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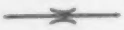
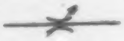
RESTRICTION, FIXED	
RESTRICTION, VARIABLE	

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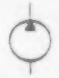
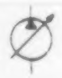
PUMP, SINGLE FIXED DISPLACEMENT	
PUMP, SINGLE VARIABLE DISPLACEMENT	
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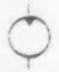
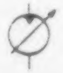
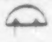
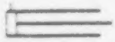
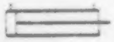
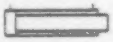
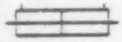
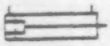
MOTOR, ROTARY, FIXED DISPLACEMENT	
MOTOR, ROTARY VARIABLE DISPLACEMENT	
MOTOR, OSCILLATING	
CYLINDER, SINGLE-ACTING	
CYLINDER, DOUBLE-ACTING	
CYLINDER, DIFFERENTIAL ROD	
CYLINDER, DOUBLE END ROD	
CYLINDER, CUSHIONS BOTH ENDS	

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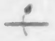
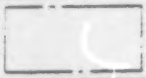
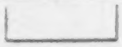
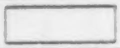
DIRECTION OF ROTATION (ARROW IN FRONT OF SHAFT)	
COMPONENT ENCLOSURE	
RESERVOIR, VENTED	
RESERVOIR, PRESSURIZED	
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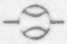
TEMPERATURE GAGE	
FLOWMETER (FLOW RATE)	
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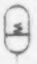
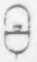
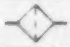
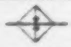
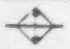
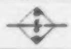
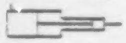
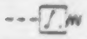
ACCUMULATOR, SPRING LOADED	
ACCUMULATOR, GAS CHARGED	
FILTER OR STRAINER	
HEATER	
COOLER	
TEMPERATURE CONTROLLER	
INTENSIFIER	
PRESSURE SWITCH	
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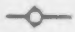
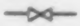
CHECK VALVE	
MANUAL SHUT OFF VALVE	
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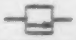
VALVE, SINGLE FLOW PATH, NORMALLY CLOSED	

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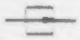
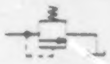
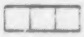
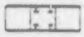
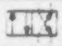
VALVE, SINGLE FLOW PATH, NORMALLY OPEN	
VALVE, MAXIMUM PRESSURE (RELIEF)	
BASIC VALVE SYMBOL, MULTIPLE FLOW PATHS	
FLOW PATHS BLOCKED IN CENTER POSITION	
MULTIPLE FLOW PATHS (ARROW SHOWS FLOW DIRECTION)	
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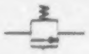
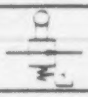
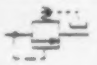
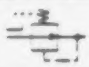
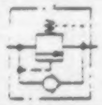
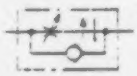
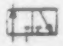
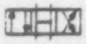
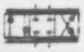
UNLOADING VALVE, INTERNAL DRAIN, REMOTELY OPERATED	
DECELERATION VALVE, NORMALLY OPEN	
SEQUENCE VALVE, DIRECTLY OPERATED, EXTERNALLY DRAINED	
PRESSURE REDUCING VALVE	
COUNTER BALANCE VALVE WITH INTEGRAL CHECK	
TEMPERATURE AND PRESSURE COMPENSATED FLOW CONTROL WITH INTEGRAL CHECK	
DIRECTIONAL VALVE, TWO-POSITION, THREE-CONNECTION	
DIRECTIONAL VALVE, THREE-POSITION, FOUR-CONNECTION	
VALVE, INFINITE POSITIONING (INDICATED BY HORIZONTAL BARS)	

Table 1. Continued.

METHODS OF OPERATION		METHODS OF OPERATION	
PRESSURE COMPENSATOR		LEVER	
DETENT		PILOT PRESSURE	
MANUAL		SOLENOID	
MECHANICAL		SOLENOID CONTROLLED, PILOT PRESSURE OPERATED	
PEDAL OR TREADLE		SPRING	
PUSH BUTTON		SERVO	

BASIC HYDRAULIC CIRCUITS

Basic hydraulic circuits are widely used to power a single actuator. This discussion centers on the operating principles of simple circuits, which also govern the operation of more complicated circuits.

CYLINDER CIRCUITS

The simplest hydraulic circuit is one used to power a single-acting cylinder. Such a circuit consists of a hydraulic power unit; a single-acting cylinder; a three-way, two-position directional control valve for directing flow to and from the cylinder; and adequate piping to transport the oil. (Such a circuit was constructed in the Laboratory section of Module FL-01, "Introduction and Fundamentals of Fluid Power.")

All hydraulic circuits are designed around the circuit actuators. In the simple single-acting cylinder circuit, the cylinder is chosen first based on the load, extension distance, and circuit pressure. The pump is chosen for proper operation in the desired pressure range. The deliver rate of the pump is chosen to give the correct operating speed of the actuator based on the volume of fluid necessary for full extension and the desired extension time. A pressure relief valve protects the pump and establishes maximum system pressure. Piping is sized to accommodate full pump delivery with an acceptable fluid velocity, usually less than 20 fps. The directional control valve (DCV) is selected to give the proper circuit functions. All components should have fluid ports large enough to maintain the fluid velocity at an acceptable value. If the ports are too small, the flow may be restricted enough to partially open the pressure relief valve and the cylinder speed will be less than desired. Turbulence in small ports will also consume power and produce heating of the hydraulic oil.

Figure 1 shows a circuit for operating a double-acting cylinder, which is slightly more complex. It is controled by a four-way DCV. If the left envelope of the valve is used, the cylinder in this circuit is retracted; if the right envelope is used, the cylinder is extended. At the end of its travel in either direction, the piston stops and oil flows through the pressure relief valve to the reservoir. The system pressure is maintained at the maximum by the pressure relief valve. A two-position valve has only two possible positions and cannot be used to stop the load at an intermediate point. The three-position valve in Figure 1 has a center blanked position for stopping the load at any desired point.

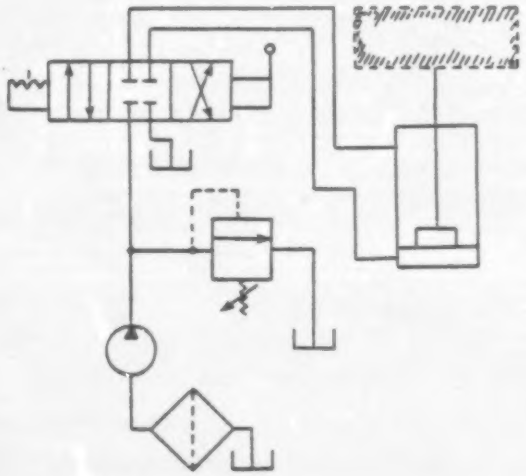


Figure 1. Three-Position, Four-Way Directional Control Valve Used to Control Piston Movement in the Cylinder.

During the retracting stroke of the double-acting cylinder, oil enters the rod end of the cylinder at the pump delivery rate. Because the rod occupies some of the volume of this end of the cylinder, the piston velocity is greater than for the extension stroke (and the force produced is less). The faster motion of the piston forces oil out of the blanked end of the cylinder at a rate greater than the pump delivery rate. Fluid conductors, which carry oil from the blanked end of the cylinder back to the reservoir, must be sized for this higher flow rate or flow restrictions may occur.

MOTOR CIRCUITS

The simplest circuit for controlling a hydraulic motor is one for a constant speed motor that rotates in only one direction. The circuit control consists of a two-way valve that turns fluid flow to the motor ON and OFF. The motor drains directly to the reservoir.

Figure 2 shows the simplest circuit for operating a reversible hydraulic motor at a constant speed. The controls of this circuit are identical to those of the cylinder circuit in Figure 1. This circuit is designed around the specifications of the fluid motor chosen.

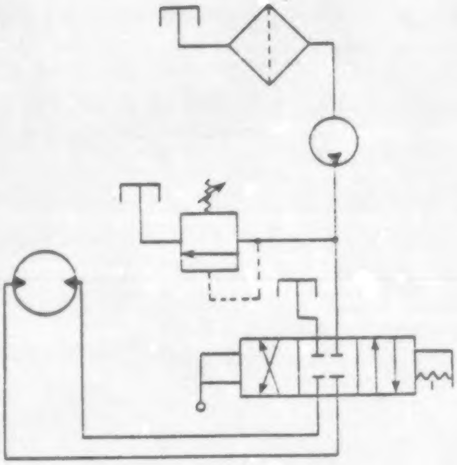


Figure 2. Closed-Center, Three-Position, Four-Way DCV Used to Control a Hydraulic Motor for Rotation in Either Direction.

SPEED CONTROL

In many circuits, the speed of operation of actuators must be controlled. This is accomplished with flow control valves, which can be applied in three ways. Any of the three methods discussed can be used to control the speed of actuators or motors.

Figure 3 shows metering-out or exhaust flow control. In this circuit, the forward movement of the piston is controlled by the adjustable orifice in the flow control, which controls the volume of oil exhausted from the cylinder on its forward stroke. The extension velocity of the piston is set by a flow control valve located between the piston exhaust port and the DCV. This valve limits the flow from the rod end of the piston and, thus, limits flow into the blank end of the piston for extension.

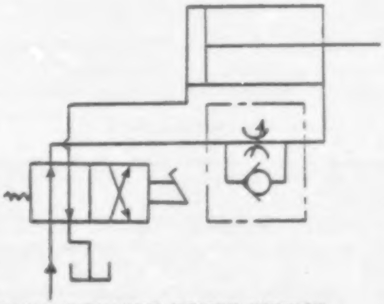


Figure 3. Metering-Out or Exhaust Flow Control.

In Figure 4, a similar flow control valve is located in the power line between the DCV and the piston and restricts flow into the blank end of the piston, thereby limiting the extension speed. This is called metering-in flow control. In both cases, a check valve is included to allow full flow around the flow control valve during the

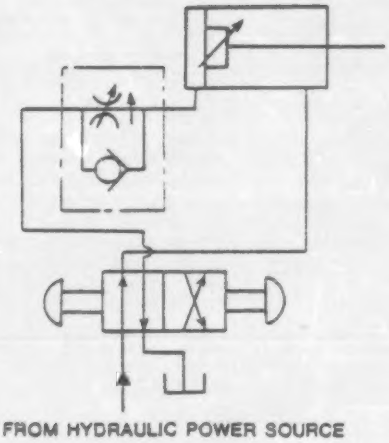


Figure 4. Metering-in Flow Control.

retraction stroke. When flow is limited in either of these ways, the excess output of the pump is returned to the reservoir by the pressure relief valve. The flow valve in Figure 3 is a noncompensated valve and will work properly only if the system pressure is maintained near the maximum value. The vertical arrow in the valve symbol in Figure 4 indicates that this valve is pressure compensated and will control the flow at any pressure. Such valves are also available with temperature compensation to maintain a constant flow as oil viscosity changes with temperature.

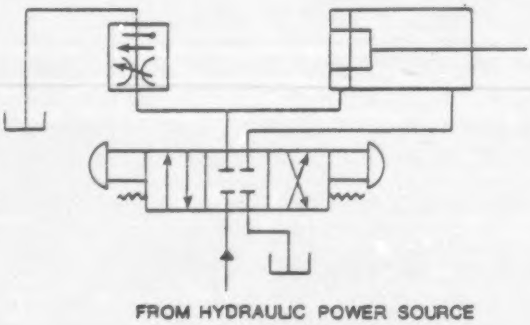


Figure 5. "Bleed-off" Method of Controlling Piston Movement in a Cylinder.

Figure 5 illustrates bleed-off flow control in which a portion of the pump delivery is passed through a flow control valve back to the tank. The cylinder speed is reduced because it only operates on the portion of the flow that is not passed by the flow control valve.

BASIC PNEUMATIC CIRCUITS

Basic pneumatic circuits are similar to basic hydraulic circuits but are somewhat simpler since the working fluid is not returned to the system. All pneumatic circuits employ the basic principles presented in the following paragraphs.

CYLINDER CIRCUITS

The basic circuit design for air cylinder operation is the same as for hydraulic cylinders except the working fluid is exhausted just past the DCV rather than being returned to the system. Figure 6 shows a pneumatic circuit for double-acting cylinder operation. Like the hydraulic circuit shown in Figure 1, this circuit allows the load to be stopped at any point along its travel. Since air is compressible, accurate positioning is not possible and the piston is likely to move if the load on it varies.

The speed of operation of the air cylinder depends on the rate at which compressed air can be delivered to one side of the piston and exhausted from the other. Since compressed air is stored in a tank under pressure, the capacity of the fluid conductors — not the compressor capacity — limits the speed of actuators. Increasing the diameter of the pipes will increase the speed of the cylinder.

This circuit also shows the filter-regulator-lubricator unit. This component should be located in the air line to each pneumatic circuit as close to the actuator as possible. In cases of a long air line from a control valve to an actuator, an additional lubricator may be required at the actuator. The remaining pneumatic circuit diagrams in this module do not show the FRL unit, but it should always be assumed to be present.

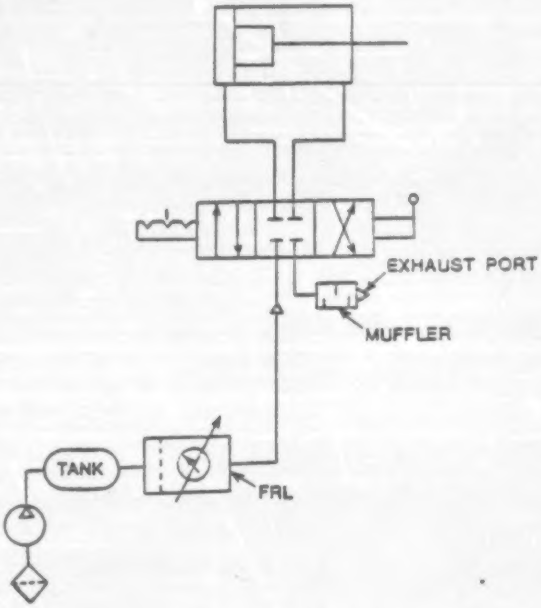


Figure 6. Three-Position, Four-Way DCV Used to Halt Piston Movement of the Cylinder at Intermediate Stops.

MOTOR CIRCUITS

The circuits for operating air motors are similar to those for hydraulic motors except that air motors usually exhaust directly to atmosphere. Figure 7 shows a slightly more complicated control scheme using push-button valves for pilot control of the DCV. This non-reversible air motor could also be operated with a manual DCV of similar design. Air motor speed varies with the load on the motor but also depends upon the rate at which air is delivered to the motor.

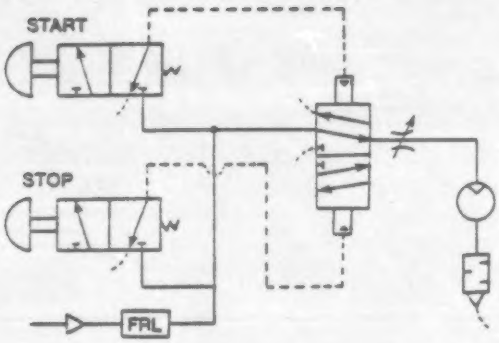


Figure 7. Push-Button Control of an Air Motor.

SPEED CONTROL

Speed control of pneumatic systems is accomplished by metering the flow into or out of the component. Pressure line metering is usually avoided with cylinders because it can result in erratic cylinder movements. Most pneumatic flow controls consist of adjustable needle valves on the exhaust side of the component.

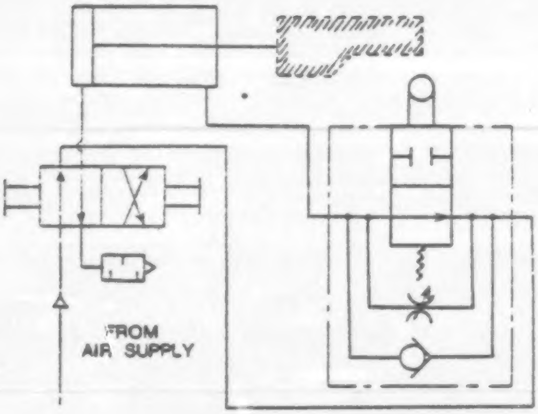


Figure 8. Cam-Operated Speed Control Used to Provide Two Different Piston Speeds.

The speed of an actuator can be varied by the circuit shown in Figure 8. The rod end of the cylinder is connected to a component containing a two-way valve, a check valve, and a metering valve. The switch is operated by a cam on the piston rod. At the beginning of the extension stroke, the two-way valve is open and the air in the rod is vented to atmosphere. This gives the greatest piston velocity. When the cam actuates the valve, air must exit the cylinder through the flow valve. The check valve allows full flow in the opposite direction for rapid retraction. This control circuit can be used to move a load at two different speeds or to decelerate the piston to reduce shocks.

The speed of air motors cannot be closely controlled unless the load is constant. The speed is usually adjusted by a metering valve on the exhaust of the air motor.

MULTI-PRESSURE CIRCUITS

Pneumatic systems often operate at several different pressures. The main air supply usually has a pressure of about 90 psig. Regulators for each circuit are set to reduce the line pressure to that required by the circuit. Pilot-controlled circuits like the one illustrated in Figure 7 often use pilot control pressures of 10 psig.

In some cases, two different working pressures are required in one pneumatic circuit. The air-powered chuck shown in Figure 9 requires a large holding force during deep rough cuts on the part being machined and a lighter holding force during finishing cuts to prevent distortion of the part. The large force is applied by actuating the right solenoid valve. This applies full circuit pressure to the rod end of the piston. When force reduction is required, the left solenoid valve is actuated, which channels lower pressure air from a second regulator to the blank end of the cylinder. This accomplishes a specific reduction in holding force. Pressure reducing valves perform the same function in hydraulic circuits.

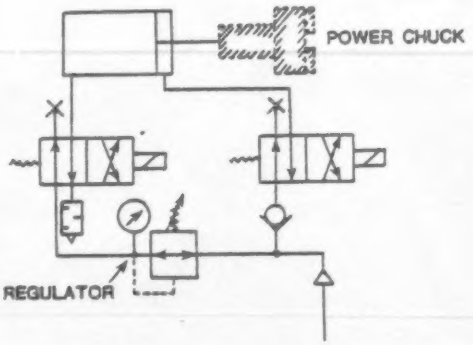


Figure 9. Pneumatic Circuit Designed for Two-Pressure Operation in Conjunction with Power Chucking Equipment.

SYNCHRONOUS MOTION

In many fluid power applications, the motion of two or more actuators or motors must be synchronized. Various methods of accomplishing synchronous motion are discussed in the following paragraphs.

HYDRAULIC CYLINDERS IN SERIES

Figure 10 shows a simple method of synchronizing two hydraulic cylinders. The cylinders are connected in series so that the oil flows from the rod end of cylinder A to the blank end of cylinder B on the extension stroke. If the cylinders are the same size, they will both extend at fixed rates, but A will extend more rapidly and move farther than B. In order to produce synchronous motion, the area of the piston in cylinder B must equal the difference in areas of the piston and rod in cylinder A. The pump must be capable of delivering a pressure that will provide the total driving force of both pistons on the piston in cylinder A. Half this force will be transmitted to the piston in cylinder B. These restrictions make this circuit undesirable for many applications.

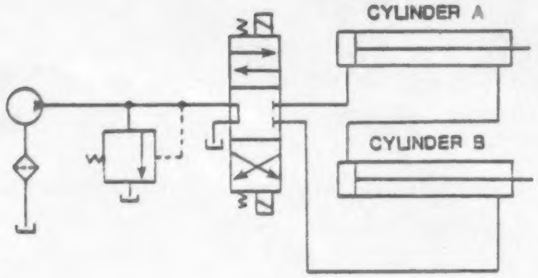


Figure 10. Cylinders Connected in Series.

FLUID MOTORS AS SYNCHRONIZERS

Figure 11 shows a simple method of synchronizing several identical hydraulic cylinders. Each cylinder is connected in series with a positive-displacement pump. The pump shafts are connected so that all pumps rotate together. The pump and cylinder combinations are connected in parallel. This produces excellent synchronization of any number of cylinders. Cylinders of different sizes can be synchronized if the pump displacement for each cylinder is changed accordingly. The major disadvantage of this system is its cost. Several other methods may be used to synchronize hydraulic cylinders.

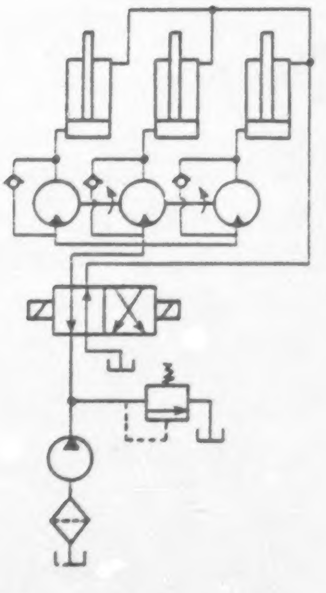


Figure 11. Synchronization of Three Hydraulic Cylinders.

AIR CYLINDERS

Since air is a compressible fluid, it cannot be used as a synchronizing medium. Air cylinders are often synchronized by using air and oil cylinders in tandem, as shown in Fiugre 12. Each air-oil cylinder consists of a double-acting air cylinder and a double-acting hydraulic cylinder with a common rod. Compressed air is delivered to all air cylinders in parallel for actuation together. The series hydradulic circuit causes all pistons to move together. This is one of the best synchronous circuits and is also used in hydraulic power systems.

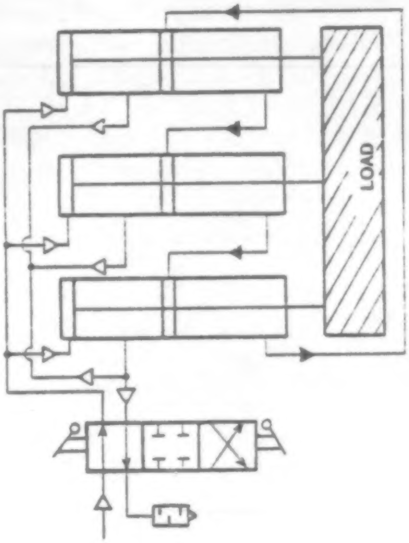


Figure 12. Synchronous Operation of Three Air-Oil Cylinders.

HYDRAULIC MOTORS

Fixed-displacement hydraulic motors can be synchronized by connecting them in series, as shown in Figure 13. If the two motors have the same displacement, they will rotate together. As with series piston circuits, the pump must be able to deliver sufficient pressure at the first motor in the circuit to drive the loads of both. Air motors cannot be synchronized.

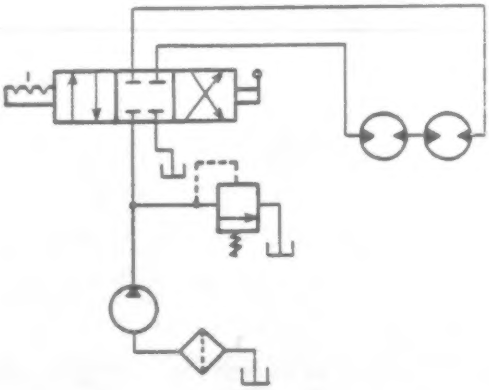


Figure 13. Two Identical Positive-Displacement Motors Connected in Series.

ACTUATOR SPEED

In some applications, the speed of fluid power actuators must be increased beyond that which is available with the simple circuits discussed earlier. This section discusses how this may be accomplished in pneumatic and hydraulic circuits.

PNEUMATIC CIRCUITS

The speed of a pneumatic actuator can be increased by increasing the air delivery capability of the high-pressure piping and controls or by decreasing resistance to airflow in the exhaust line. Figure 14 shows a quick-exhaust valve used to increase the operating speed of an air hammer. With the valves in the position shown, air enters the rod end of the cylinder and raises the load. When the DCV is moved to the other position, the air in the pilot chamber of the exhaust valve is exhausted through the DCV. The spring return of the exhaust valve pushes its spool upward, venting the rod end of the cylinder directly to atmosphere at a location near the cylinder.

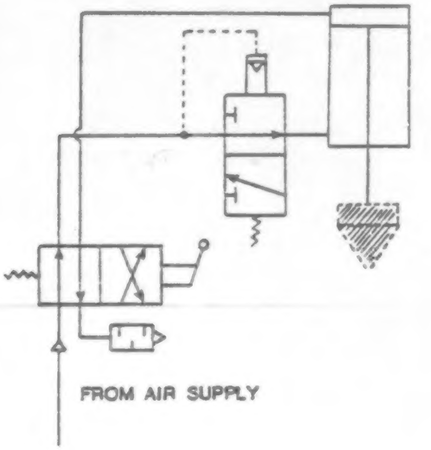


Figure 14. Quick-Exhaust Valve Used to Increase Piston Speed in the Cylinder.

HYDRAULIC CIRCUITS

The speed of hydraulic actuators is limited by the rate at which the pump can deliver hydraulic fluid. Speed can be increased only if the fluid delivery rate can be increased. Economics and efficiency often demand that this be accomplished without increasing pump capacity. Figure 15 shows a simple method of increasing the extension velocity of a double-acting hydraulic cylinder. This is called a regenerative circuit because the oil in the rod end of the cylinder is channeled to the blank end during extension. The extra volume of oil extends the cylinder more rapidly. Because both ends of the cylinder are at equal pressure during extension, the effective force-producing area is the area of the piston rod. Thus, the regenerative circuit trades maxmium force for increased speed. Other methods of providing the increased flow rate for rapid actuator movement during part of a cycle are discussed in the following section.

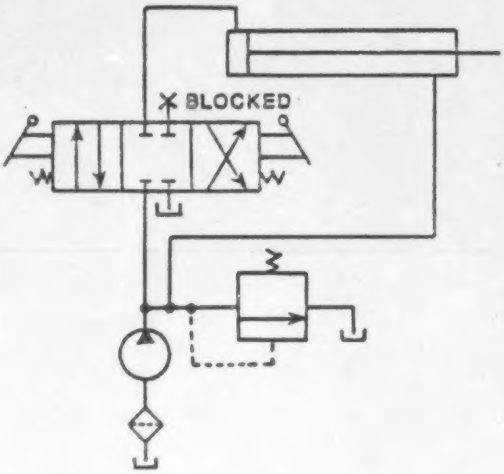


Figure 15. Regenerative Circuit.

Figure 16 shows an accumulator used to increase the operating speed of a hydraulic cylinder in both directions. When the DCV is actuated, the flow from the pump is supplemented by flow from the accumulator to increase the flow rate into the cylinder. The increase in speed is dependent upon the capacity of the accumulator and the size of the connecting pipes. Pipes and valves between the accumulator and the cylinder should be enlarged to accommodate the increased flow rate. The pressure relief valve in this circuit may be replaced by a pump unloading valve, as described in the next section of this module.

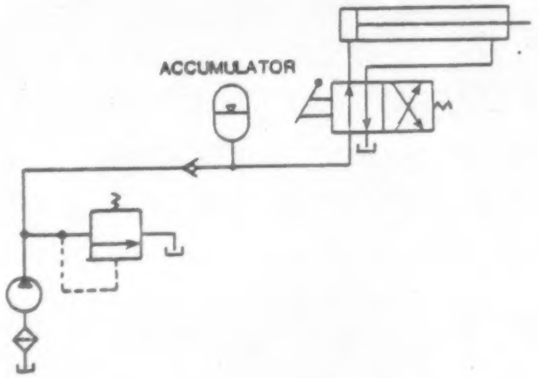


Figure 16. Accumulator as an Auxiliary Power Source.

ENERGY EFFICIENCY IN HYDRAULIC CIRCUITS

Fluid power systems have varying power requirements during different parts of their operating cycle. In pneumatic systems, the compressor stores the working fluid under pressure and, when the energy is used, the power requirements have little effect on system efficiency. Hydraulic pumps, on the other hand, deliver fluid at a constant flow rate, whether the system requires it or not.

The power required by the pump drive increases with delivery pressure, as described in Module FL-04, "Pumps and Compressors." When a hydraulic system with a pressure relief valve requires no oil flow, the pressure relief valve allows the pump delivery to flow back to the reservoir while maintaining the maximum system pressure. This requires the maximum power input on the pump drive. The input energy is converted to heat in the oil by the pressure relief valve. Thus, when such a system does not work, it consumes the maximum amount of energy and creates the greatest amount of heating to hasten the decomposition of the oil and seals. Higher pressures and temperatures also promote pump wear and failure. The energy efficiency of a hydraulic system can be increased by reducing the amount of fluid flowing through pressure relief valves. This may be accomplished in several ways, depending on system requirements.

PUMP UNLOADING

Pump unloading in a hydraulic system consists of reducing the pump delivery pressure to near atmospheric in order to reduce its input power requirements to the minimum value while the pump output is not needed. One simple method of unloading a pump is to use a three-position, four-way DCV with a center connection that returns the pump output directly to the tank. If a circuit such as the one shown in Figure 1 is used for holding a load in a fixed position for any length of time, this simple change can greatly increase its efficiency and the life of the oil and components.

Figure 17 shows the use of a pump unloading valve. This is a pilot-operated valve that allows the pump output to flow to the reservoir at atmospheric pressure as long as a preset pressure exists at the pilot port. The check valve permits fluid from the system actuators to flow through the unloading valve and maintains the pressure in the system. This valve unloads the pump any time its output is not needed to move the piston.

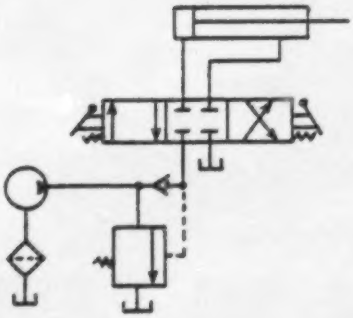


Figure 17. Simple Pump Unloading Circuit.

DOUBLE-PUMP HYDRAULIC SYSTEMS

Hydraulic systems for operating presses often require a large flow rate at low pressure for extending the piston until contact is made with the work piece and a low flow rate at a much higher pressure for the forming operation. This can be accomplished with one large, high-pressure pump; however, such pumps are very expensive and have other drawbacks as well. During rapid extension, they would operate at low power. During the pressing operation, most of their fluid delivery would be forced through a pressure relief valve.

The most economical solution to this problem for most such applications is the double-pump circuit shown in Figure 18. Both pumps can be driven by the the same power source. During rapid extension of the piston at low pressures, both pumps deliver fluid to the system. When the rod encounters the work piece, the pressure increases, thereby closing the check valve above the low-pressure pump and opening the pump unloading valve. The high-pressure pump produces the necessary pressure at a low flow rate. The excess flow from this pump goes through the pressure relief valve, but this fluid volume is usually so small that there is little heating effect in the total fluid volume of the system.

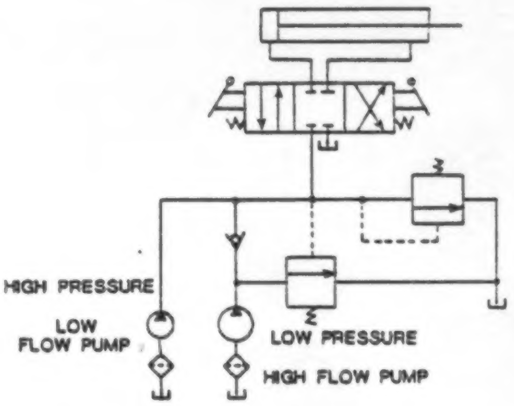


Figure 18. Double-Pump Hydraulic System.

USE OF ACCUMULATORS TO IMPROVE SYSTEM EFFICIENCY

Figure 19 shows the use of an accumulator to reduce the size of pump necessary for a hydraulic system in order to increase system efficiency. The accumulator increases the actuator speed above the speed available with the pump alone and acts as an auxiliary power source for holding and compensating for leakage. A pressure-actuated electrical switch turns the pump off when it is not needed, reducing the power consumption to zero during extended holding operations.

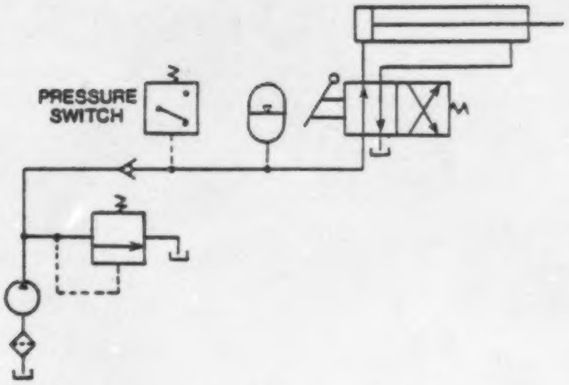


Figure 19. Accumulator as a Leakage Compensator.

USE OF ACCUMULATORS IN HIGH-LOW CIRCUITS

Figure 20 shows an energy efficient dual power hydraulic circuit using an accumulator as an auxiliary power source. The figure shows the circuit with the valves positioned for rapid extension of the piston. Fluid flow is provided to the cylinder by the high-pressure pump, the low-pressure pump, and the accumulator. When the pressure in the cylinder rises above the pressures of the accumulator and low-pressure pump, the check valves in the lines from these components close. This pressure also actuates the pilot-controlled DCV directing the output of the low-pressure pump to the actuator to recharge it. The check valve below the accumulator prevents any reverse flow from the accumulator and allows the use of a pump unloading valve for the low-pressure pump. An unloading valve is also used with the high-pressure pump. The check valve above it maintains pressure for holding operations while the pump is unloaded.

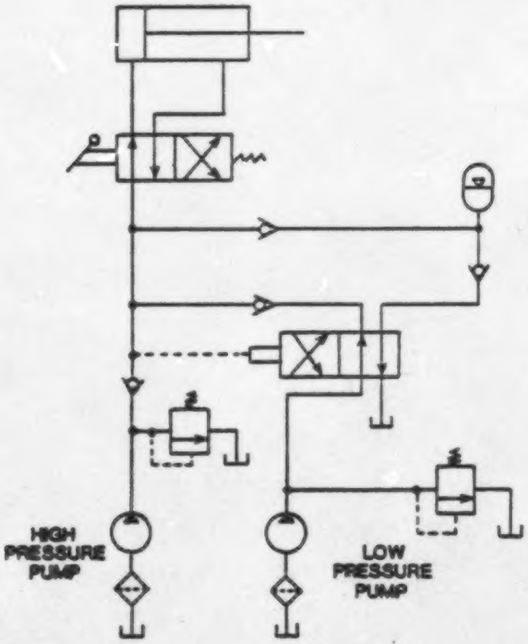


Figure 20. Accumulator as an Auxiliary Power Source.

SUMMARY

Fluid power circuits are always designed around the circuit actuators and the functions they perform. In pneumatic systems, the speed of an actuator is determined by the flow rates in the air delivery system and the resistance to flow in the exhaust ports. In a hydraulic system, the maximum flow rate is the delivery rate of the pump, unless special circuits or components are used to provide auxiliary flow. The piping of hydraulic systems is sized to present little resistance to fluid flow.

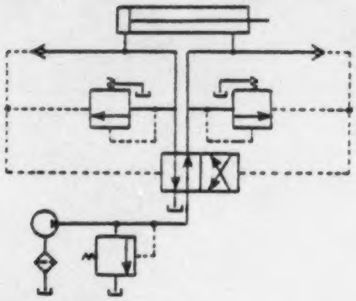
Speed control is accomplished in hydraulic circuits by the use of flow control valves in three locations. In pneumatic circuits, flow control is usually applied to the exhaust port for smoother cylinder operation. Hydraulic cylinders can be synchronized by connecting appropriate cylinders in series or by using paralleled positive-displacement pumps as metering devices to supply each cylinder with the same flow rate. Compressed air cannot be used as a synchronizing fluid, but air cylinders can be synchronized by using air-oil tandem cylinders with a closed series hydraulic circuit connecting the oil cylinders. Fixed-displacement hydraulic motors can be synchronized by simply connecting them in series. The speed of hydraulic cylinders can be increased by using a regenerative circuit, by using an accumulator as an auxiliary power source during fast extension, or by using a dual pump system.

The key to increasing the energy efficiency of a hydraulic system is to reduce the amount of oil that flows through pressure relief valves. This is usually accomplished by unloading the pump so its delivery pressure is atmospheric pressure.

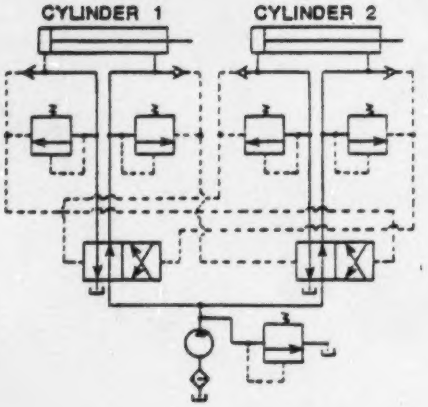
EXERCISES

1. Describe the operation of the following circuits, starting with the cylinders fully retracted in each case. Explain the purpose of each component.

a.



b.



2. Redraw the circuit shown in Figure 1, showing the use of a pump unloading valve and an accumulator acting as an auxiliary pump source and leakage compensator.
3. Draw a simple fluid circuit showing the synchronous operation of three double-rod hydraulic cylinders.
4. Consult the library, and draw and describe at least one method of synchronizing the fluid power actuators not discussed in this module.
5. Explain three methods of speed control in hydraulic circuits.
6. In the regenerative circuit in Figure 15, the rod area is one-half the piston area. If the pump delivers fluid at 20 gpm, what is the flow rate into the blanked end of the cylinder during extension? Explain.

7. Explain how each of the following can increase the efficiency of a fluid power system:
   a. Pump unloading valve
   b. Double-pump system
   c. Accumulators used as auxiliary power sources

LABORATORY MATERIALS

Hydraulic power unit
Four-way, three-position DCV with blanked center
Double-acting hydraulic cylinder with friction-type loading device
Check valve
Pressure relief valve
Unloading valve
Connecting hoses
Electrical wattmeter
Stopwatch
English scale

LABORATORY PROCEDURES

1. Construct the fluid power circuit shown in Figure 1 of this module.
2. Connect the wattmeter to the electrical input of the hydraulic power unit.
3. Operate the circuit to assure proper operation. Set tension on loading device to produce near the maximum pressure during the retraction stroke.
4. Operate the circuit and measure the quantities listed in the Data Table. All powers are electrical input power measured in watts.
5. Calculate the total energy consumed by the power unit during a cycle, including a holding time of 20 seconds. Convert the answer to foot-pounds. (746 J = 550 ft•lb.)

6. Calculate the mechanical work done by the cylinder during the cycle. This can be done by first determining the force exerted by the piston for extension and retraction strokes by multiplying the pressure for each stroke times the effective area for that stroke. Work for each stroke is the product of force and piston stroke. Express the total work for the cycles in foot-pounds.
7. Calculate the overall efficiency of the cylce based on the electrical input energy and the mechanical work done.
8. Disassemble this circuit and construct a similar circuit using a pump unloading valve. This is the circuit from Exercise 2 without the accumulator. This circuit must include a check valve in the pump outlet line. Have instructor inspect the circuit. Do not change the tension on the cylinder loading device.
9. Perform Steps 4 through 7 using this circuit.
10. Compare the operation and efficiency of the two circuits.

DATA TABLE

DATA TABLE.

Circuit with Pressure Relief Valve:
- Piston stroke:
- Extension time:
- Retraction time:
- Power during extension:
- Power during retraction:
- Power during holding:
- Pump delivery pressure during extension:
- Pump delivery pressure during retraction:
- Pump delivery pressure during holding:

Calculations:
- Energy used for cycle with holding time of 20 seconds:
- Mechanical work done:
- Cycle efficiency:

Circuit with Pump Unloading Valve:
- Piston stroke:
- Extension time:
- Retraction time:
- Power during extension:
- Power during retraction:
- Power during holding:
- Pump delivery pressure during extension:
- Pump delivery pressure during retraction:
- Pump delivery pressure during holding:

Calculation:
- Energy used for cycle with holding time of 20 seconds:
- Mechanical work done:
- Cycle efficiency:

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GLOSSARY

Air-oil cylinder: A tandem cylinder consisting of an air cylinder and an oil cylinder with a common rod, used for synchronizing the operation of pneumatic cylinders.

Bleed-off flow control: Hydraulic flow control in which a portion of the pump delivery is allowed to flow directly to the reservoir.

Double-pump circuit: A hydraulic circuit using a high-volume, low-pressure pump for rapid cylinder extension and a low-volume, high-pressure pump for exerting large forces on a load that is nearly stationary.

Metering-in flow control: Flow control in which the flow rate of oil entering a cylinder or motor is controlled.

Metering-out flow control: Flow control in which the flow of exhaust fluid from a component is controlled.

Pump unloading: A method of increasing system efficiency by delivering the full flow of the pump to the reservoir with atmospheric pressure at the pump outlet port while no fluid flow is required by the system.

Regenerative circuit: A hydraulic circuit in which the oil exiting the rod end of the cylinder on the extension stroke enters the blanked end to increase the rate of extension.

TEST

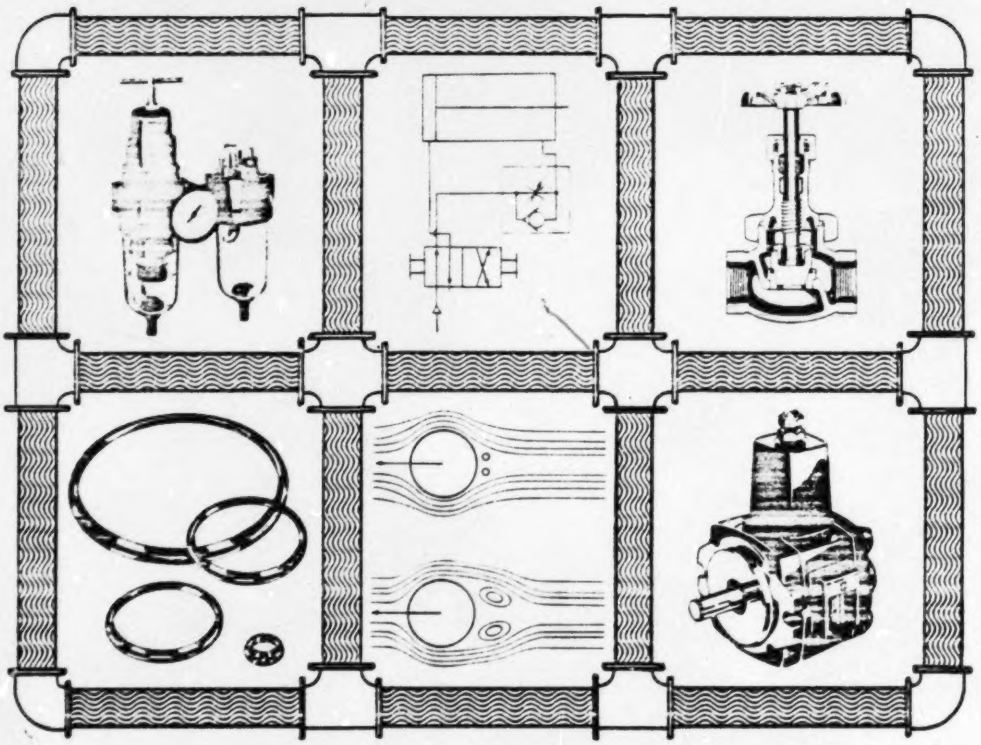
1. In a properly designed basic hydraulic circuit, the speed of an actuator depends on ...
   a. the delivery rate of the pump.
   b. the resistance to fluid flow in the high-pressure fluid conductors.
   c. the resistance to fluid flow in the exhaust lines.
   d. Both a and c are true.
   e. All of the above are true.
2. In a properly designed basic pneumatic circuit, the speed of an actuator depends upon ...
   a. the capacity of the compressor.
   b. the resistance to fluid flow in the compressed air delivery lines.
   c. the resistance to fluid flow in the exhaust lines.
   d. Both b and c are true.
   e. All of the above are true.
3. Which of the following speed control methods is most common in pneumatic systems?
   a. Metering-in flow control
   b. Metering-out flow control
   c. Bleed-off flow control
   d. Both a and b are used about equally.
   e. All are commonly used.
4. The first component selected in the design of basic hydraulic systems is the ...
   a. pump.
   b. control valve.
   c. cylinder.
   d. piping.
   e. pressure relief valve.
5. In the most common type of simple hydraulic system, the pump requires the greatest input power during ...
   a. piston extension against a load.
   b. piston retraction with no load.
   c. holding at full extension with no piston load.
   d. holding at full retraction with no piston load.
   e. Both c and d are true.

6. Hydraulic cylinders cannot be synchronized by which of the following means?
    a. Connecting two cylinders in series with the piston area of one equal to the difference in piston and rod areas of the other
    b. Connecting identical double-rod cylinders in series
    c. Using identical tandem cylinders with the forward cylinders of each tandem cylinder connected in a closed series loop
    d. Using hydraulic pumps with their output shafts connected as metering devices for cylinders
    e. None of the above are true. (All may be successfully used.)
7. The speed of a hydraulic actuator cannot be increased by ...
    a. using an accumulator as an auxiliary power source.
    b. using a low-pressure, high-volume pump for part of the extension cycle.
    c. increasing the size of the fluid conductors.
    d. increasing the maximum pump delivery pressure.
    e. Both c and d are true.
8. The most important factor in increasing the energy efficiency of a hydraulic power system is ...
    a. decreasing the amount of fluid flowing through pressure relief valves.
    b. decreasing the amount of energy lost because of resistance to flow in fluid conductors.
    c. using lower operating pressures.
    d. using higher operating pressures.
    e. Both a and c are equally important.
9. Which of the following circuits does not normally include a check valve?
    a. Pump unloading circuit
    b. Double-pump circuit
    c. Accumulator used as a leakage compensator
    d. Exhaust flow control circuit
    e. None of the above are true. (All normally require check valves.)
10. Replacing a pressure relief system with a pump unloading system will usually result in ...
    a. lower oil pressures.
    b. higher oil temperatures.
    c. longer oil life.
    d. longer pump life.
    e. Both c and d are true.

ENERGY TECHNOLOGY

CONSERVATION AND USE

FLUID POWER



MODULE FL-08

TROUBLESHOOTING FLUID CIRCUITS

CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

INTRODUCTION

Troubleshooting fluid circuits is the process of locating and correcting malfunctions and failures in fluid power systems. In many cases, this can be difficult and frustrating because the cause of many fluid power problems may not be readily apparent. This is particularly true of hydraulic systems where a variety of problems may arise in the components of the hydraulic power unit. The variety of fluid power components and the variations and complexities of fluid power circuits make descriptions of detailed troubleshooting techniques for specific circuits and components a task beyond the scope of this module. The intent of this module is to give general guidelines that can be applied to troubleshooting in any fluid power system. Topics discussed include the causes of most fluid power failures, measuring instruments used for troubleshooting, and common measurement techniques. A variety of failure symptoms are listed and the possible causes of each system are given. The discussion also includes safety circuits, precautions necessary for troubleshooting safety circuits, and safety regulations.

In the laboratory, the student will perform troubleshooting procedures on fluid power circuits and prepare a report of the condition of the circuit and any problems located.

PREREQUISITES

The student should have completed Module FL-07, "Fluid Power Circuits."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Explain the purpose of troubleshooting in fluid power systems.
2. List and explain seven causes of failure in fluid power systems. Include the steps that must be taken to prevent each.
3. List and explain 10 mistakes that are sometimes made in fluid power installations.

4. List the three quantities usually measured in hydraulic circuit troubleshooting, and describe the instruments used for the measurement of each.
5. Draw and label a diagram of a hydraulic circuit tester and explain its operation.
6. Draw circuits showing testing of fluid power components and explain what problems each test will reveal.
7. Given symptoms of malfunctions in fluid power systems, identify possible malfunctions that would result in each symptom.
8. List and explain the seven steps that should be followed in troubleshooting procedures.
9. Draw and label diagrams of a hydraulic circuit using an accumulator as an emergency power source and a two-handed pneumatic control circuit. Explain the operation of each circuit.
10. Perform troubleshooting procedures on pneumatic and hydraulic circuits and prepare a report on the condition of each circuit.

MAINTENANCE AND TROUBLESHOOTING IN FLUID POWER SYSTEMS

Fluid power maintenance is the routine inspection, repair, and replacement of components and materials in a fluid power system to ensure the proper and efficient operation of that system and to prevent unscheduled stoppages. Troubleshooting is the collection of methods for locating and correcting a problem that develops in the system. Maintenance and troubleshooting functions tend to overlap. For example, a routine maintenance procedure is often to listen to the pump and note any unusual noise, as such noise is often the first sign of developing problems. Noise is also an important indicator of the location of a problem during troubleshooting.

Fluid power systems are easily damaged because of the high working forces and the close tolerances of surfaces moving under high pressure. They require more maintenance than any other power delivery system. Procedures discussed in this module are primarily intended to identify failures in the system. They are often a part of maintenance procedures since many circuit problems are found during maintenance. The troubleshooting techniques described here are employed to locate the cause of the problem. Emergency troubleshooting can be avoided by implementing a well-planned maintenance program.

CAUSES OF FAILURE

In a well-designed, installed, and maintained fluid power system, failures during normal operation are rare. Unfortunately, many systems are subject to built-in errors and neglect. The following discussion centers on factors that contribute to malfunction in fluid power systems.

Dirt

The most common cause of failure of working components in fluid power systems is contamination of the working fluid with particles that destroy seals and metal surfaces in sliding contact. Contamination of the working fluid results in scored pistons, rods, and cylinders, deterioration of pump seals, and worn valve seats. Particles may stick in small openings and valve components and cause malfunctions. If a dirty working fluid is used, leaks will develop quickly and components are likely to seize. The life expectancy of all components decreases as system cleanliness decreases.

Heat

Heat is not often a problem in pneumatic power systems, as the working fluid acts as a cooling medium and is exhausted to the atmosphere. In hydraulic power systems, the oil carries the heat away from components, but the heat energy is contained in the recirculating oil and must be removed through the reservoir walls or by heat exchangers. Heat causes rapid oxidation of hydraulic oil and can damage packings and seals and cause spool valves to stick. Operation at higher temperatures reduces the lubricating properties of oils and may result in more rapid pump wear or seizure in high-pressure, high-speed pumps.

Misapplication

One common cause of component failure in fluid power systems is misapplication of components. Cylinders are often damaged because they are subjected to strains and shock loads for which they were not designed. The use of cylinders with cast iron covers in applications with high hydraulic shocks is sure to lead to failures. Long piston rods may be bent if subjected to side loads or if used to develop forces beyond their rated capacity. In selecting fluid power actuators, the buyer should provide the supplier with detailed information concerning actuator load and use. For most applications, several types of actuators are available with varying costs and reliabilities. Inadequate components are always less expensive initially, but are often quite costly in the long run.

Improper Fluids or Poor Fluid Maintenance

A variety of problems can result in a hydraulic system when a fluid is used whose properties are not suitable for the system. If the viscosity is too low, the pump may wear more quickly and excessive leakage may occur; if it is too high, pump cavitation and sluggish operation may result. If the fluid is not compatible with seals or other materials in the system, chemical reactions may destroy components. Oil containing water or that is highly oxidized will promote rust and corrosion. In pneumatic systems, component failure often results because of inadequate lubrication.

Faulty Installation

The following problems may result from incorrect installation procedures:

1. Flow controls may be reversed, limiting flow in the wrong direction.
2. Directional controls may be connected incorrectly. This is more probable in complicated systems involving numerous pilot connections.
3. Piping may be too small. This is particularly likely when accumulators are used for rapid piston extension in hydraulic systems. All piping must be large enough to provide full fluid flow at velocities less than 20 fps. Using conductors that are too small in pneumatic systems will cause the actuator to be sluggish.
4. Actuators may be installed with too much back pressure. Long runs of exhaust piping in pneumatic circuits may reduce the actuator speed. In hydraulic systems, small return lines on the location of an actuator so it must return oil to a reservoir located above it will not usually slow the component but will rob the system of power because of the pressure drop along the line.
5. The installation of a hydraulic power unit in an enclosed area with poor ventilation is likely to cause overheating. The reservoir must be surrounded by freely flowing air for proper oil cooling.
6. Failure to make all drain connections to valves and other components may result in improper operation. Many hydraulic components have nonpositive seals that leak a small amount of oil during operation. If this oil is not returned to the tank, the back pressure in the component will increase and the component will not operate properly.
7. Actuators may not be firmly anchored. Even a small amount of "play" in the mount of a working cylinder can result in serious damage because of the large forces involved.
8. Misalignment of piston rods will result in side thrusts on pistons and rods that may damage seals or cause uneven wear of components. Misalignment of rotary shafts lead to the same problems.
9. Lack of protection for piston rods in dirty locations may shorten the life of rods and seals.
10. Improper anchoring of pipes, tubing, and hoses can result in undesirable conductor motion in high-pressure hydraulic systems and can lead to conductor failure. All piping should be securely anchored.

11. Leaks may occur because of improperly connected pipes and fittings or because of improperly installed seals. All system leaks should be repaired immediately.

Poor Maintenance

Most fluid power failures can be attributed to inadequate maintenance procedures. A good maintenance program should locate developing problems before they become severe and should prevent damage due to fluid contamination. In pneumatic systems, the most important maintenance procedures are the cleaning of air filters and the refilling and checking of air-line lubricators. In hydraulic systems, the most important maintenance item is proper fluid maintenance. This includes cleaning or replacing filters and replacing oil at specific intervals. The condition of all fluid power actuators should be checked regularly. Maintenance procedures for each fluid power system are unique to that system and are dependent upon system design, application, and location.

Improperly Designed Circuits

Occasionally, a fluid power circuit may be incapable of performing its task because of errors in system design. Problems resulting from design errors include pressures or flow rates that are too low, lack of speed control, overheating, and actuators that are too small to deliver the required force.

SYMPTOMS OF FAILURE

Table 1 lists some of the more common symptoms of failures in fluid power systems and the malfunctions in the system that could lead to those symptoms. Problems that occur only in pneumatic circuits are indicated by the letter P; those that occur in hydraulic circuits only are followed by the letter H; and those common to both systems have no designation.

TABLE 1. COMMON FAILURES IN FLUID POWER SYSTEMS AND THEIR POSSIBLE CAUSES.

Component	Problem	Possible Cause
Cylinders	Excessive wear on one side of piston rod	• Misalignment or side thrust • Incorrect mounting style
	Bent piston rod	• Excessive side load on end of piston rod • Cylinder used above rated pressure
	Slow or erratic motion of actuator	• Air in system (H) • Fluid viscosity too high (H) • Insufficient lubrication (P) • Worn or damaged pump (H) • Leakage through actuator seals • Leakage through valves • Faulty or dirty flow control valves • Faulty check valve • Low fluid level in reservoir (H) • Defective pressure relief valve (H) • Lack of lubrication (P)
	Cylinder does not move	• Load on the cylinder too great • System pressure too low • Cylinder cushion seized • Defective cylinder seal • Check valve in backwards • Faulty pump (H) • Stuck directional control valve • Pressure relief valve stuck open (H)
Valves	Solenoid or pilot-operated directional control valve does not operate	• Valve actuator received no input signal • Defective valve actuator • Dirt caused valve to stick • Lack of lubrication (P)
	Sequence valve does not open to permit proper actuator sequence	• Valve pressure setting too high • Valve spring or seals have failed • Dirty valve

Table 1. Continued.

	Speed control valve does not function properly	• Wrong valve setting • Valve reversed in fluid line • Dirty valve • Line pressure fluctuates and valve is not pressure compensated
Hydraulic Power Unit (Hydraulic Only)	Noisy pump	• Air in fluid • Excessive oil viscosity • Misalignment of pump and drive shafts • Clogged or dirty filter • Damaged pump • Excessive pump speed • Chattering relief valve • Loose or damaged inlet line
	No pressure	• Ruptured hydraulic line • Pressure relief valve stuck open • Pump turning in the wrong direction • Full pump flow returned to tank through faulty valve or actuator
	Low or erratic pressure	• Air in fluid • Low oil level in reservoir • Defective or worn pump • Defective pressure relief valve • Defective actuator
	Overheating of the hydraulic oil	• Continuous operation of pressure relief valve • Insufficient airflow for cooling reservoir • Reservoir too small • Dirty fluid • Heat exchanger inoperative • Piping sized too small • Incorrect fluid for system

TROUBLESHOOTING HYDRAULIC CIRCUITS

Troubleshooting hydraulic circuits is often a complicated and confusing task for several reasons. Many failures have simple and obvious causes, but others may be difficult to diagnose and explain. One component often fails to function properly because of a hidden fault in another component that was caused by still another fault in the total system. Hydraulic system troubleshooting must be approached in a systematic way in order to locate and correct all problems associated with a system failure. This process usually includes several possible causes based on system performance. Suspected components are then tested separately and the condition of each is determined. Tests include disassembly and inspection of components and measurements of pressure, flow rate, and temperature at various points in the system during the operating cycle. Troubleshooting procedures should not be terminated with the location of a single fault in the system, particularly if that fault is related to fluid type, condition, or temperature. If one component fails because of these factors, others are likely to be affected also.

MEASURING EQUIPMENT

The most common measurements in hydraulic system troubleshooting are of pressure and flow rate. Oil temperature is also measured frequently.

Pressure measurements are usually made with Bourdon-type pressure gauges. These are available in a wide range of pressure capabilities and some have provisions for measuring pressures below atmospheric in the suction line. Pressure gauges usually read directly in psig for pressure lines and inches of vacuum for suction lines.

Flow measurements can be made with several types of flowmeters. The most common type consists of a metering float contained in a tapered tube. The float is actually made of metal and is pulled down by gravity. Fluid flow around the float forces it upward. The height of the float indicates the flow rate on a scale on the side of the transparent flow tube. This type of flowmeter must be mounted vertically with the flow upward in order to be effective. A similar device uses a lightweight piston that is spring-loaded and can be used in a horizontal position. Turbine flowmeters and piston and rotary positive-displacement type meters may also be used. In many systems, a flowmeter is permanently mounted in the pump delivery line for flow monitoring. A pressure gauge is often permanently mounted in the same location. If a flowmeter is not available, the flow rate for systems or components with low flow rates can be determined by catching the return oil in a graduated container for a measured time and calculating the volume flow rate. This procedure may be particularly useful in checking the drain lines of spool valves for valve leakage.

Temperature can be measured at various points in the system with any convenient thermometer. The most common measurement is of oil temperature in the reservoir. If hot spots are suspected in the system, temperatures may be measured just downstream of the suspected trouble spot. One method that may be successfully used is to bring the sensor of a contact thermometer into close contact with the fluid conductor and wrap the area with a thermal insulating material.

A portable hydraulic circuit tester consists of a flowmeter, pressure gauge, thermometer, and loading valve. It is used to test pumps in systems that do not have built-in metering and for tests at other points in the system. Figure 1 shows a hydraulic circuit tester in a circuit. This device measures fluid flow rate, pressure, and oil temperature at the point of connection in the circuit. In Figure 1, the tester is installed for pump measurements and may also be used to deliver specific pressures and to measure total system pressure and flow rate as components are actuated. The flow rate of a specific component can be measured by connecting the tester in series with that component.

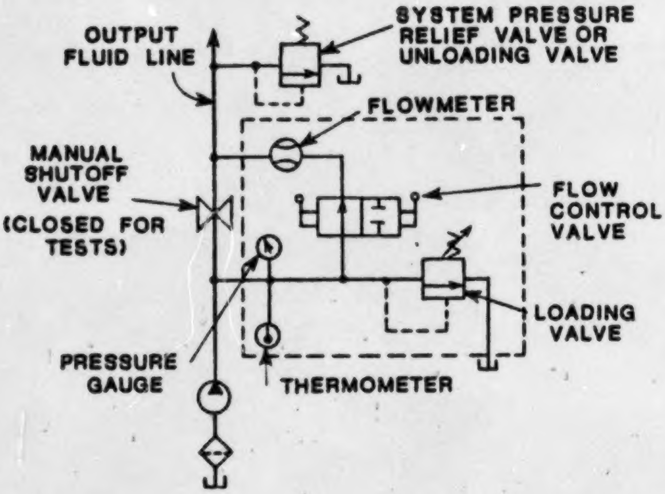

OUTPUT FLUID LINE
SYSTEM PRESSURE RELIEF VALVE OR UNLOADING VALVE
FLOWMETER
MANUAL SHUTOFF VALVE (CLOSED FOR TESTS)
FLOW CONTROL VALVE
LOADING VALVE
PRESSURE GAUGE
THERMOMETER

Figure 1. Hydraulic Circuit Tester.

MEASUREMENT TECHNIQUES

The performance of the pump can be evaluated by using the circuit tester connected as shown in Figure 1. The pump test procedure is outlined in Module FL-04, "Pumps and Compressors," and consists primarily of measuring the change in delivery rate as delivery pressure is varied from atmospheric to the system working pressure. This data can be used to determine the volumetric efficiency of the pump. A comparison of the result to the pump specifications and past test results will indicate the amount and rate of wear of the pump.

The pressure relief valve can be tested with the same circuit connections. This is accomplished by blocking the flow of oil in the output fluid line. All fluid must then pass through either the pressure relief valve or the loading valve of the circuit tester. A graph of flow rate versus pressure for the pressure relief valve can be drawn from the data collected. The operation of other pressure-actuated valves, such as sequence valves, may be tested in a similar manner by appropriate connections of the circuit tester.

The circuit shown in Figure 1 can also be used to measure total leakage of the circuit during holding operations. This is accomplished by setting the loading valve to produce a pressure at which the pressure relief valve allows no flow. Oil passing through the flowmeter during holding then indicates total leakage. Checking the leakage rate at different points in the machine cycle will often indicate a particular group of components as having a high leakage, but usually does not pinpoint the problem. For example, if the leakage is high with a cylinder extended but low with the same cylinder retracted, either the rod seals of the cylinder or the seals of the valves in that part of the system are leaking.

Actuators can be checked for leaks by measuring fluid flow to or from the actuator at full extension and full retraction. Directional control valves can be checked for leaks by measuring the flow through their drain lines during operation. Flow control valves can be checked by measuring flow through them during the system cycle. For assurance of correct measurements for a particular component, the circuit tester or flowmeter must be placed so it measures fluid flow to or from that component only.

In all test procedures, a list of components to be tested should be prepared before testing begins. Each component should be tested and the test results recorded. Permanent records should be kept of all test procedures and results. These may prove invaluable in future system tests. Maintenance procedures should be modified to prevent the recurrence of the problem. If necessary, the system should be modified for more trouble-free operation. The purpose of the troubleshooting procedure is not only to place the system back in operation but also to eliminate the need for future troubleshooting.

TROUBLESHOOTING PROCEDURES

Troubleshooting techniques vary greatly from one hydraulic power system to another, but some general procedures should always be followed. The following steps are essential parts of all troubleshooting procedures. Experienced technicians accomplish some of these so automatically that they fail to notice the significance of the step. Beginners should write down and check their troubleshooting plan before beginning to assure all steps are covered and no procedural errors are included.

1. Operate the system and record operating characteristics. Observations made by the system operator should also be recorded. Remember that excessive or unusual noise is often an indication of malfunctions.
2. Define the component relationships within the system. Obtain or draw a system schematic and trace fluid flow through the system during each phase of system operation. A clear understanding of the purpose and operation of each circuit component is essential for troubleshooting.
3. Determine the pressures and flow rates to be expected at various points in the system. Note these on the system schematic and in detailed test procedures. This will allow the troubleshooter to spot problems immediately during tests.
4. Based on the operating characteristics and system schematic, establish a step-by-step troubleshooting procedure. List the components to be tested, the conditions under which each is to be tested, the quantities to be measured, and the test method including the location of measuring equipment.
5. Conduct system and component tests according to the established troubleshooting sequence. In emergency situations requiring the quickest possible return of the system to operation, the troubleshooting sequence may be terminated when the faulty component is located. If this is done, the test sequence should be completed as soon as possible to locate other possible faults in the system. If time permits, the troubleshooting sequence should be completed as planned even though one trouble spot has been located. This may save another system failure in the near future.
6. Repair or replace faulty components and operate the system with no applied load. If no problems are apparent, operate the system with normal load and observe its operation. Additional measurements may be required at this point.
7. Record all test procedures and results in a notebook for future reference. If changes are indicated in maintenance procedures or system design, record these and initiate the changes as soon as possible.

TROUBLESHOOTING PNEUMATIC CIRCUITS

Troubleshooting in pneumatic circuits is usually less complicated than in hydraulic circuits. All hydraulic system problems associated with the pump, reservoir, pressure relief valve, and fluid return are absent. Many of the problems with actuators and valves are the same as with the hydraulic systems, as indicated by Table 1. Pneumatic systems have two major problems that are not present in hydraulic systems. The first is lack of lubrication because of lubricator failure or inadequate oil supply. The other is the presence of contamination in the air delivery lines that may be carried to the component through a defective filter. Air lines typically contain water, dirt that has come in through the compressor, and pipe scale. Thus, air-line filters are required near every branch circuit. The failure of either filter or lubricator will cause problems with both valves and actuators.

Troubleshooting techniques for pneumatic systems are essentially the same as for hydraulic systems. Measurements are made with pressure gauges and flowmeters. Since filter-regulator-lubricator units often contain pressure gauges, pressure tests may be conducted very easily. Problems in the compressor and delivery system can be identified quickly by measuring the available pressure and flow rates at various work stations. Since there are no fluid return lines in compressed air systems, all leakage rates must be measured on the high-pressure side. Pneumatic conductors should be inspected for leaks and bad connectors.

SAFETY CONSIDERATIONS

The safety of personnel must be a consideration in the design, operation, and maintenance of any fluid power system. There can be no compromise in fluid power circuits where safety is concerned. The high fluid pressures, large forces, and high speed operations all present serious safety hazards, and maintenance and troubleshooting procedures are often far more hazardous than normal system operation.

SAFETY CIRCUITS

Several fluid power circuit features are often included as safety precautions to protect operating personnel. Figure 2 shows an accumulator used as an emergency power source for automatically retracting a piston in case of power failure in the system. The rod end of the cylinder is connected to the accumulator and maintained at the maximum working pressure. A pressure relief valve is included in this part of the system to return oil to the reservoir during the extension stroke. The effective area of the cylinder is the area of the piston minus the area of the rod, since full pressure is applied to both sides of the piston. The solenoid-actuated valve operates the circuit and is also part of the safety system. If there is an electrical power failure, this valve is actuated by spring force to connect the blank end of the cylinder to the drain. The energy stored in the accumulator retracts the piston. If any component in the system fails resulting in lowered system pressure, the pressure of the accumulator circuit will automatically retract the piston.

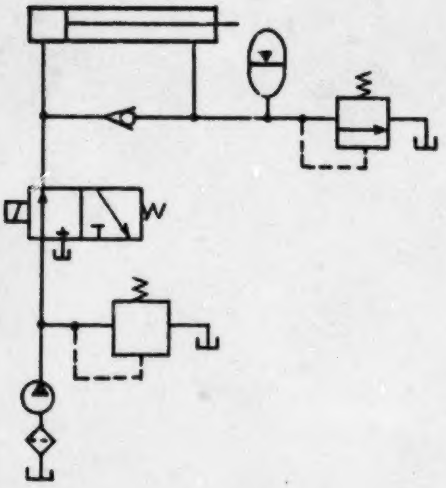


Figure 2. Accumulator as an Emergency Power Source.

During troubleshooting operations, safety circuits often present special hazards. In this circuit, a failure that completely shuts the system down leaves high-pressure hydraulic oil in the accumulator, resulting in a potential hazard to the troubleshooter. Testing of this system may require that the accumulator be drained.

Figure 3 shows a two-handed safety control circuit often used for the operation of pneumatic presses. The piston can be extended only if both push buttons are depressed at the same time. If either is released, the piston automatically retracts. The push buttons are located so that they cannot be pushed while any part

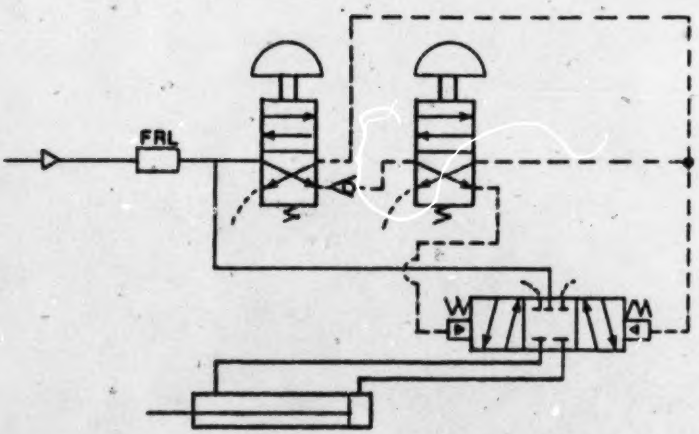


Figure 3. Two-Handed Safety Control Circuit.

of the operator's body is in the path of the piston rod.

Maintenance operations on such a circuit may require that one of the buttons be locked in the depressed position during some test procedures. Such procedures should be conducted carefully, and the button should be released immediately after each test run.

SAFETY PROCEDURES AND REGULATIONS

The Occupational Safety and Health Administration (OSHA) has established safety standards that apply to industry locations where hydraulic and pneumatic equipment is operated. Detailed information on OSHA standards and requirements may be found in OSHA publication 2072, General Industry Guide for Applying Safety and Health Standards, 29 CFR 1910. These standards deal with the following categories.

1. Workplace standards. This category includes the safety of floors, entrance and exit areas, sanitation, and fire prevention. Hydraulic equipment must be maintained in a clean and leak-free condition to meet these standards.
2. Machines and equipment standards. Important items in this category include machine guards, inspection and maintenance techniques, safety devices, and the mounting, anchoring, and grounding of fluid power equipment.
3. Materials standards. These standards specify the acceptable levels of toxic fumes, explosive dust particles, and atmospheric contamination. Ventilation requirements and methods of handling solvents used in cleaning fluid power systems and components are included.
4. Employee standards. These include employee training, personal protection equipment, and medical and first aid services.
5. Power source standards. Special safety standards are applied to all industrial power sources, including fluid power sources.
6. Process standards. Special standards are established for many industrial processes including welding, spraying, dipping, machining, and abrasive blasting. These standards do not apply directly to fluid power but influence the design of fluid power systems used in such applications.
7. Administrative standards. Industries are required to post statements of the rights and responsibilities of both employees and the industry and to keep safety records on accidents.

SUMMARY

Maintenance and troubleshooting operations in fluid power systems employ many of the same techniques. Troubleshooting techniques are intended to locate malfunctions in the system, to correct them, and to prevent their recurrence by modification of the system or maintenance procedures. Troubleshooting is best accomplished during scheduled maintenance periods, and better maintenance programs result in less emergency troubleshooting to restore system operation after breakdowns.

The most common cause of system failures in both pneumatic and hydraulic systems is dirt in the working fluid. In pneumatic systems, this is followed closely by lack of lubrication. Common problems in hydraulic systems include low oil levels in the reservoir and poor oil condition.

Troubleshooting techniques include identifying the probable trouble spots and checking the operation of each component by pressure, flow rate, and temperature measurements. Future problems may often be avoided by checking every item on the list of suspected components because more than one component is likely to be involved in many system problems.

Safety standards and regulations should be followed during both system operation and maintenance.

EXERCISES

1. List and explain seven causes of failure in fluid power systems. Include the steps to be taken to prevent the recurrence of a failure resulting from each.
2. List and explain 10 common mistakes in fluid power installations.
3. Draw and label a hydraulic circuit tester and explain its operation.
4. Draw, label, and explain the following safety circuits. Include the potential hazards for a technician during troubleshooting procedures.
    a. Accumulator as an emergency power source
    b. Two-handed safety control circuit
5. Draw a schematic of a fluid power circuit using a directional control valve, two sequence valves, and two flow control valves to control the

operation of two hydraulic cylinders. The speed of each piston is to be controlled on the extension stroke but not on the retraction stroke. The cylinder that extends last also retracts last. Discuss the probable causes of the following symptoms in this circuit:

a. Actuators operate in the proper sequence, but both are sluggish during extension and retraction.

b. The actuator that extends first operates properly, but the second actuator is sluggish on both extension and retraction.

c. One actuator extends too rapidly and retracts too slowly.

d. The second actuator extends slowly and erratically but retracts properly.

e. Both actuators have a tendency to be erratic or jerky in operation. This is accompanied by unusual noises apparently coming from the actuators and piping.

6. For each set of symptoms listed for the circuit in Problem 5, write a list of test procedures that will reveal any problems in the system.

7. Draw a schematic of a hydraulic circuit in which a three-position, spring-centered directional control valve is used to control a cylinder for positioning a heavy load on a horizontal rail. A flow control valve is used to give the same piston velocity for both extension and retraction. Discuss the probable causes of the following failure symptoms in this circuit:

   a. Piston will extend but will not retract.
   b. Piston extends and retracts too slowly.
   c. Piston extends too slowly but retracts at the proper speed.
   d. Piston retracts too slowly but extends at the proper speed.
   e. Piston extends too slowly and retracts too rapidly.

8. For each set of symptoms listed for the circuit in Problem 7, write a list of test procedures that is most likely to return the system to proper operation in the shortest time.

9. Redraw the circuit in Problem 7 with an accumulator installed as an auxiliary power source for moving the cylinder in either direction. Explain how this inclusion changes each of the test procedures in Problem 8.

LABORATORY MATERIALS

Hydraulic power unit

Hydraulic circuit tester or appropriate flowmeter, pressure gauge, themometer, and loading valve

Hydraulic components to include directional control valves, pressure relief valve, sequence valves, flow control valves, and actuators

Connecting hoses

Mechanical load for hydraulic power system

Notebook

LABORATORY PROCEDURES

In this laboratory, the student will troubleshoot a hydraulic power system. The system may be assembled by the instructor prior to the lab or may be built by the student according to directions supplied by the instructor. The system may contain either design faults or worn or inoperative components.

1. Assemble the system as indicated in the instructions provided by the instructor, using the designated components. Attach the actuator to the mechanical load as specified.
2. Operate the system according to instructions and observe system operation. Note any symptoms of failure or problems in the laboratory notebook.
3. Prepare a schematic diagram of the circuit. List the functions of the major components and the sequence of control operations in the circuit.
4. Determine the flow rates and pressures to be expected at key points in the circuit throughout the operating cycle based on the schematic and the pressure and flow rate from system design data. The rated delivery of the pump will usually be given on the pump data plate. The pressure can be determined by dividing the maximum load of the system by the area of the working piston. Record pressures and flow rates on the circuit schematic. Identify the conditions necessary for each data point.
5. Establish a step-by-step troubleshooting procedure for this system. List components to be tested, test procedures, and expected results.
6. Conduct all tests in a safe manner. Record all test results in the laboratory notebook.

7. Identify and explain faults in the system and the conditions that have caused these faults.
8. Replace faulty components or correct the circuit assembly for proper operation. Test the circuit with no load and with its normal working load to assure proper operation.
9. Record changes necessary for proper operation of the circuit without the recurrence of this problem. Include circuit and component changes and recommended maintenance procedures. The completed notebook should contain a history of troubleshooting techniques, the results of all tests, evaluation of problems, and all recommendations concerning the system.
10. Discuss briefly how this system could be made more energy efficient. (See Module FL-07, "Fluid Circuits.")

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GLOSSARY

Emergency hydraulic power source: A hydraulic power system using an accumulator for the automatic retraction of a piston in case of power failure.

Hydraulic circuit tester: A testing device for hydraulic troubleshooting that includes a pressure gauge, a flowmeter, a thermometer, and a circuit loading valve.

Troubleshooting: A collection of techniques for locating problems in fluid power systems, returning the systems to operation, and determining the cause of the problem so that recurrence may be prevented.

Two-handed control circuit: A safety control circuit used in press applications in which the operator must use both hands to actuate the press while standing clear of the machine.

1. The most common cause of failure of working components in a hydraulic power system is ...
   a. misapplication of the component.
   b. dirt in the system.
   c. improper circuit design.
   d. overheating of seals.
   e. None of the above are true.
2. A major cause of actuator failure in pneumatic systems that is usually not a problem in hydraulic systems is ...
   a. lack of lubrication.
   b. side loading of piston rods.
   c. excessive temperatures.
   d. Both a and c are true.
   e. None of the above are true.
3. The two quantities that must be measured for troubleshooting of hydraulic systems are ...
   a. oil temperature and flow rate.
   b. oil temperature and pressure.
   c. oil pressure and flow rate.
   d. oil viscosity and pressure.
   e. oil viscosity and flow rate.
4. In order to check the operation of a pressure relief valve ...
   a. oil flow to the rest of the system must be blocked.
   b. a flowmeter must be connected between the pressure relief valve and the reservoir.
   c. a pressure gauge must be connected between the pump outlet and the pressure relief valve.
   d. Both a and c are true.
   e. All of the above are true.
5. Overheating of the hydraulic fluid does not indicate which of the following possible problems?
   a. Piping sized too small
   b. Pressure relief valve set to maintain a pressure that is too high
   c. Insufficient airflow for cooling the reservoir

d. Excessive leaks through spool valves
e. Reservoir sized too small

6. In a hydraulic circuit, an actuator is operated by a sequence valve that directs fluid to it after another part of the cycle is completed. The piston speed is controlled by a fluid flow valve in series with the cylinder for exhaust metering during extension. If the piston will not extend, which of the following is not a possible cause?
   a. Flow valve is installed backwards.
   b. Pressure setting of sequence valve is too high.
   c. Pressure setting of pressure relief valve is too low.
   d. Both a and c are true.
7. In emergency troubleshooting to return a system to service when an actuator is sluggish or erratic, which of the following steps should be taken before any of the others?
   a. Replace the actuator.
   b. Check the pump output and volumetric efficiency.
   c. Consult the circuit schematic and identify all components controlling cylinder operation.
   d. Replace directional control valves in the circuit.
   e. Measure the fluid flow rate to the actuator.
8. In a hydraulic power system, all actuators operate too slowly. Which of the following could not cause this problem?
   a. Pressure relief valve is leaking.
   b. Pressure setting of pressure relief valve is too low.
   c. Pump seals have worn, reducing the volumetric efficiency.
   d. Fluid level in the reservoir is too low, allowing air to enter the suction line.
   e. Both b and d are true.
9. Which of the following is true of a hydraulic press circuit using an accumulator as an emergency power source for automatically retracting the piston in case of a power failure?
   a. The accumulator must be connected to the rod end of the cylinder through a check valve.
   b. A check valve must be located directly after the pump output.
   c. The pressure relief valve must be replaced with a pump unloading valve.

d. At a given maximum system pressure, the maximum force developed by the piston will be lower than for a similar system without an accumulator.

e. None of the above are true.

10. Which of the following are not specified by OSHA as safety requirements for fluid power systems?

a. Cleanup for all spilled fluids to prevent fire hazards and falls

b. Secure mounting and anchoring of all actuators

c. Adequate ventilation during the use of cleaning solvents

d. Provisions for training operating personnel and provisions for first aid services

e. All of the above